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Schaeffer et al.

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- (54) **WELDING ELECTRODE WIRES HAVING ALKALINE EARTH METALS**
- (71) Applicant: **Lincoln Global, Inc.**, Santa Fe Springs, CA (US)
- (72) Inventors: **John Benjamin Schaeffer**, Rocky River, OH (US); **Steven R. Peters**, Huntsburg, OH (US); **Badri K. Narayanan**, Highland Heights, OH (US); **Yen-Chih Liao**, Richmond Heights, OH (US)
- (73) Assignee: **LINCOLN GLOBAL, INC.**, Santa Fe Springs, CA (US)

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- (22) Filed: **May 16, 2018**

Bajic, Nikola, et al. "The Advantages of Using Activated Flux-Cored Wire Compared to Solid Wire in the Mag Welding Process from the Aspect of Metallurgical Characteristics" *Metalurgija* 53.3 (2014): pp. 361-364.

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Primary Examiner — Thien S Tran
(74) *Attorney, Agent, or Firm* — David J. Muzilla; Knobbe Martens

Related U.S. Application Data

- (63) Continuation-in-part of application No. 15/353,520, filed on Nov. 16, 2016, now Pat. No. 10,668,572.

- (57) **ABSTRACT**

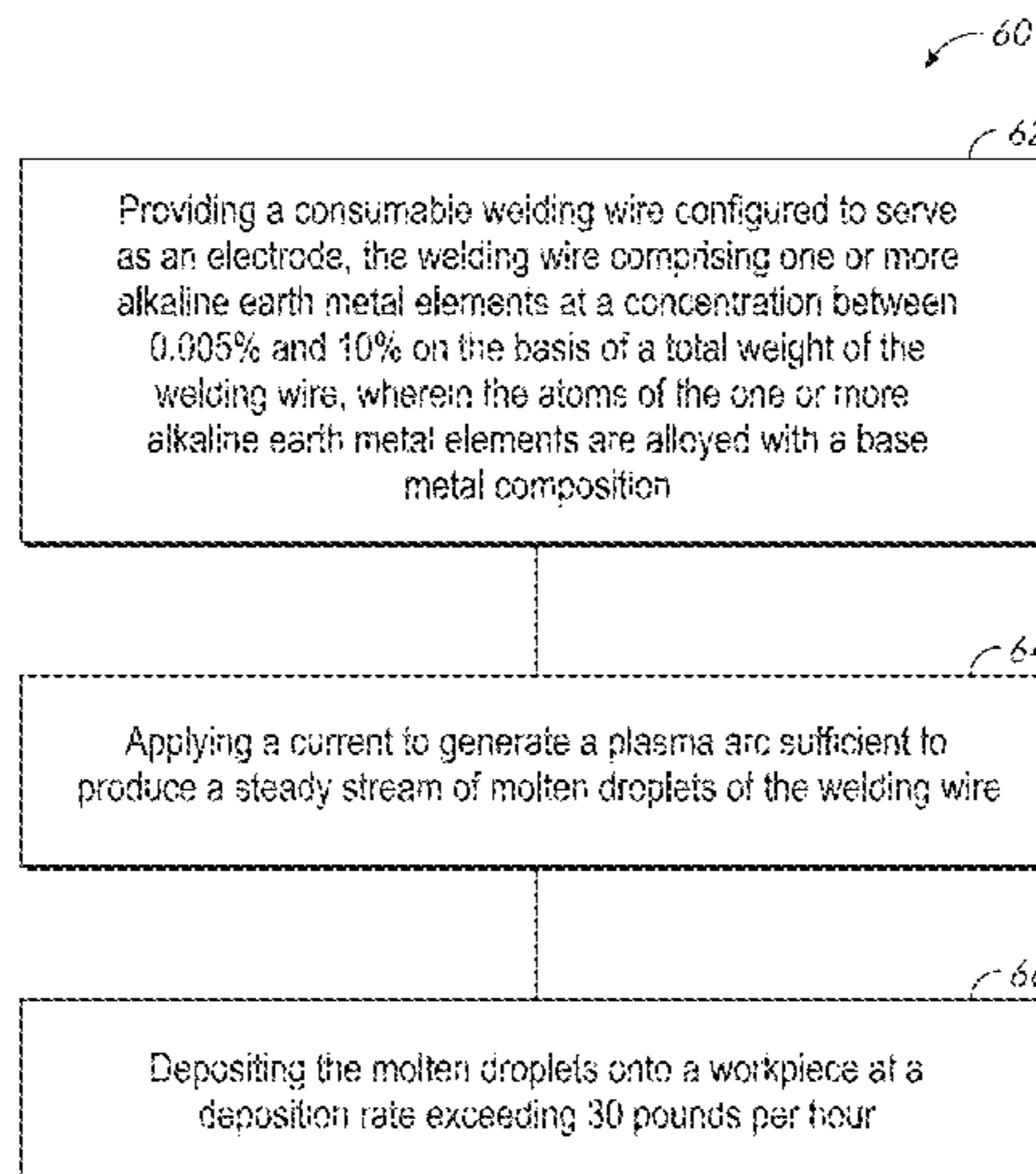
- (51) **Int. Cl.**
B23K 9/173 (2006.01)
B23K 9/26 (2006.01)
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The disclosed technology generally relates to welding, and more particularly to a consumable welding wire for metal arc welding, and a method and a system for metal arc welding using the consumable welding wire. In one aspect, a method of arc welding includes providing a welding wire comprising one or more alkaline earth metal elements. The method additionally includes applying power to the welding wire to generate a plasma arc sufficient to melt the welding wire. The method further includes depositing molten droplets formed by melting the welding wire onto a workpiece at a high deposition rate while regulating to maintain a substantially constant power delivered to the plasma arc.

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- (58) **Field of Classification Search**
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See application file for complete search history.

9 Claims, 11 Drawing Sheets



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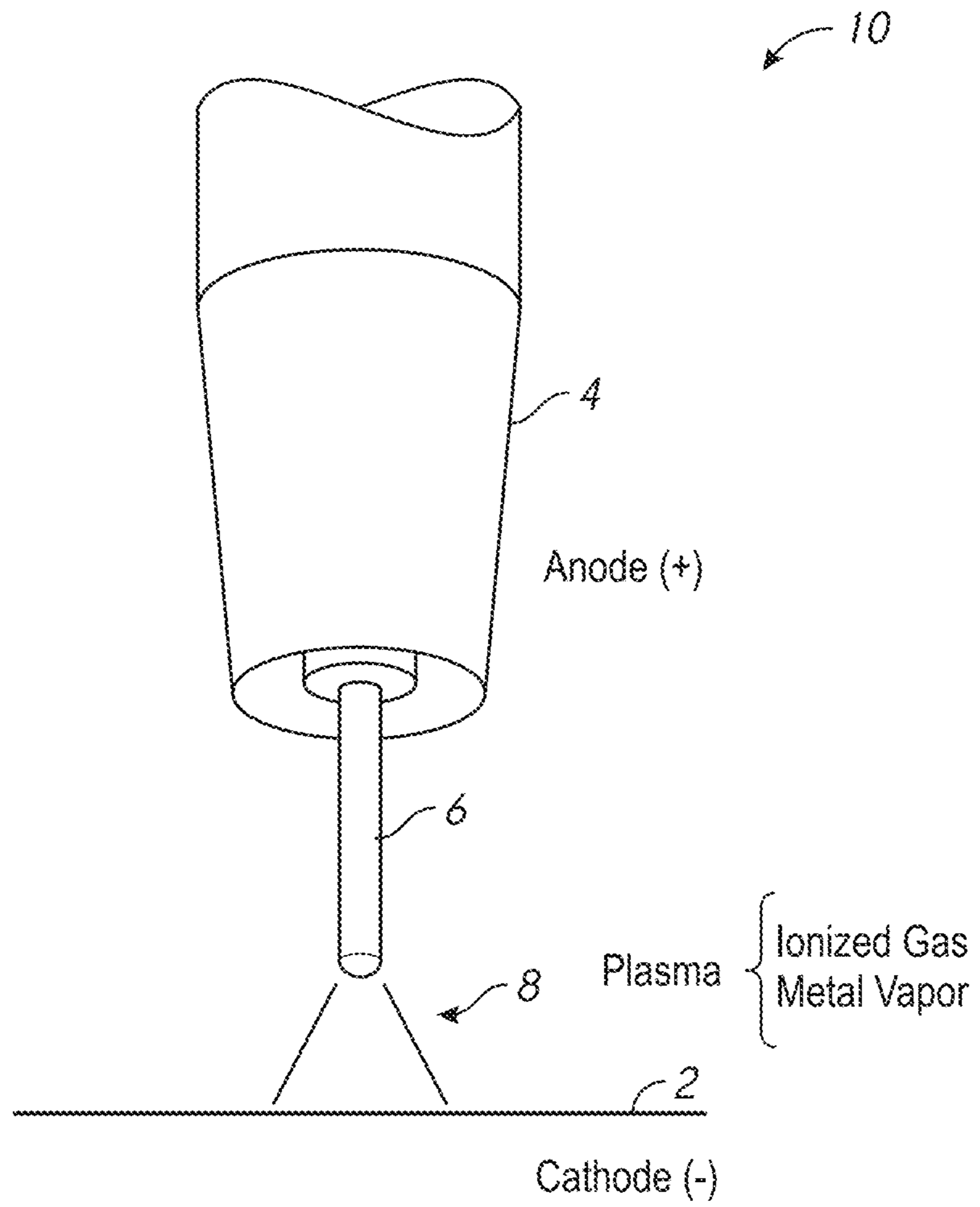


FIG. 1

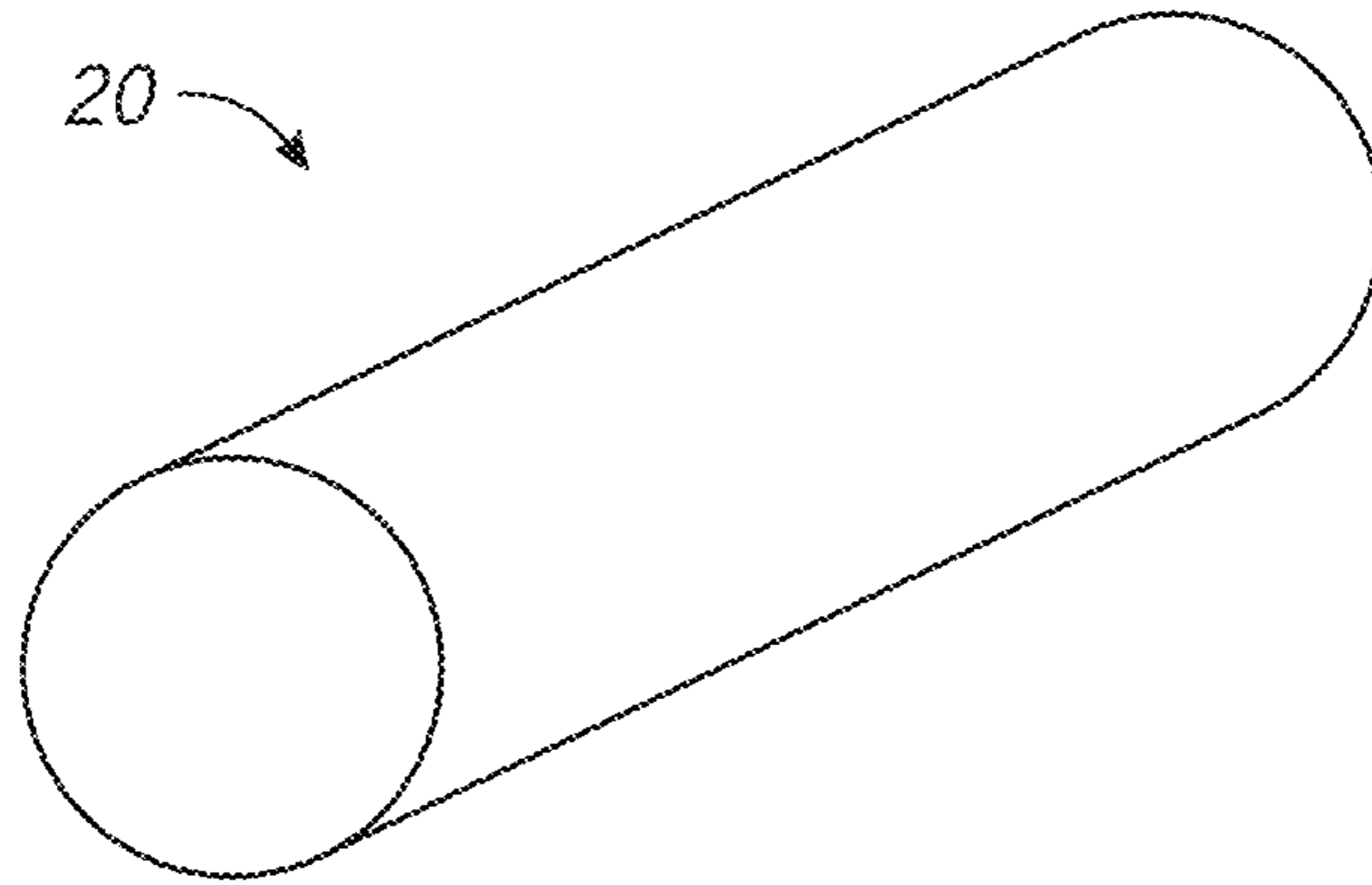


FIG. 2A

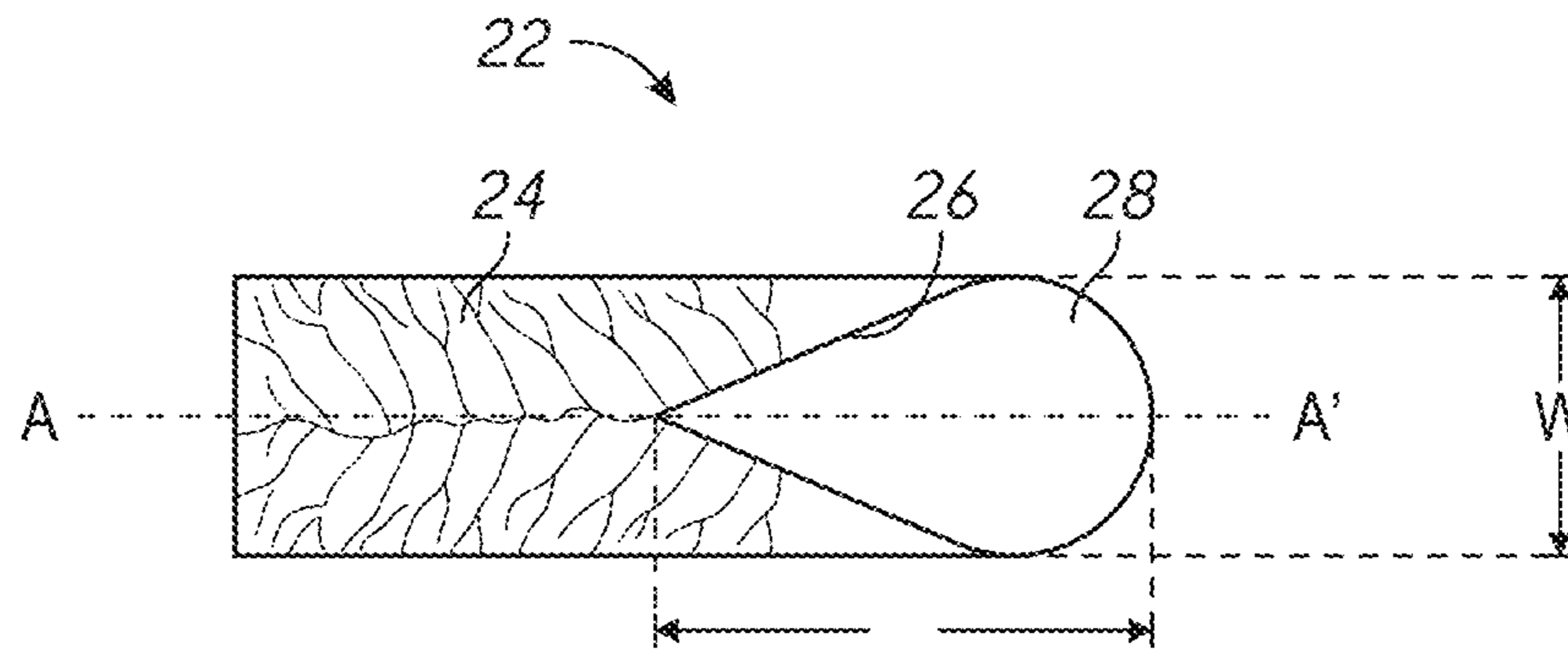


FIG. 2B

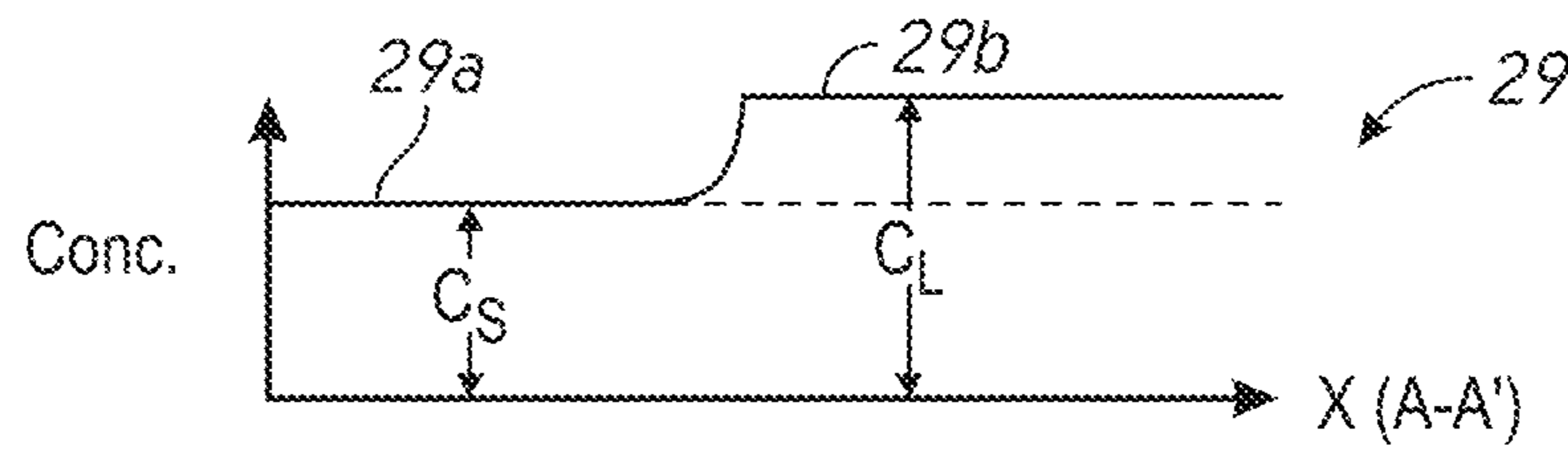


FIG. 2C

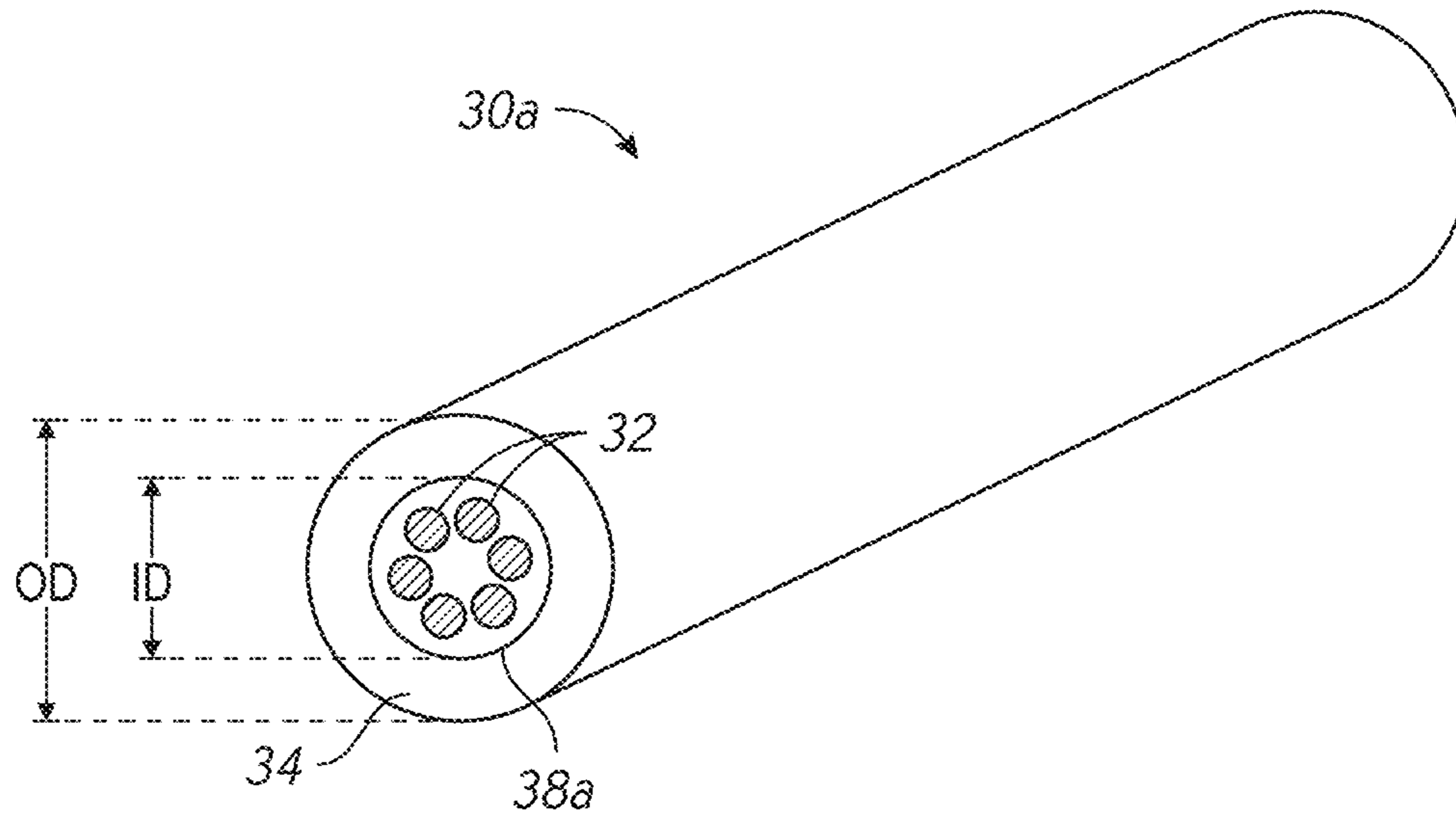


FIG. 3A

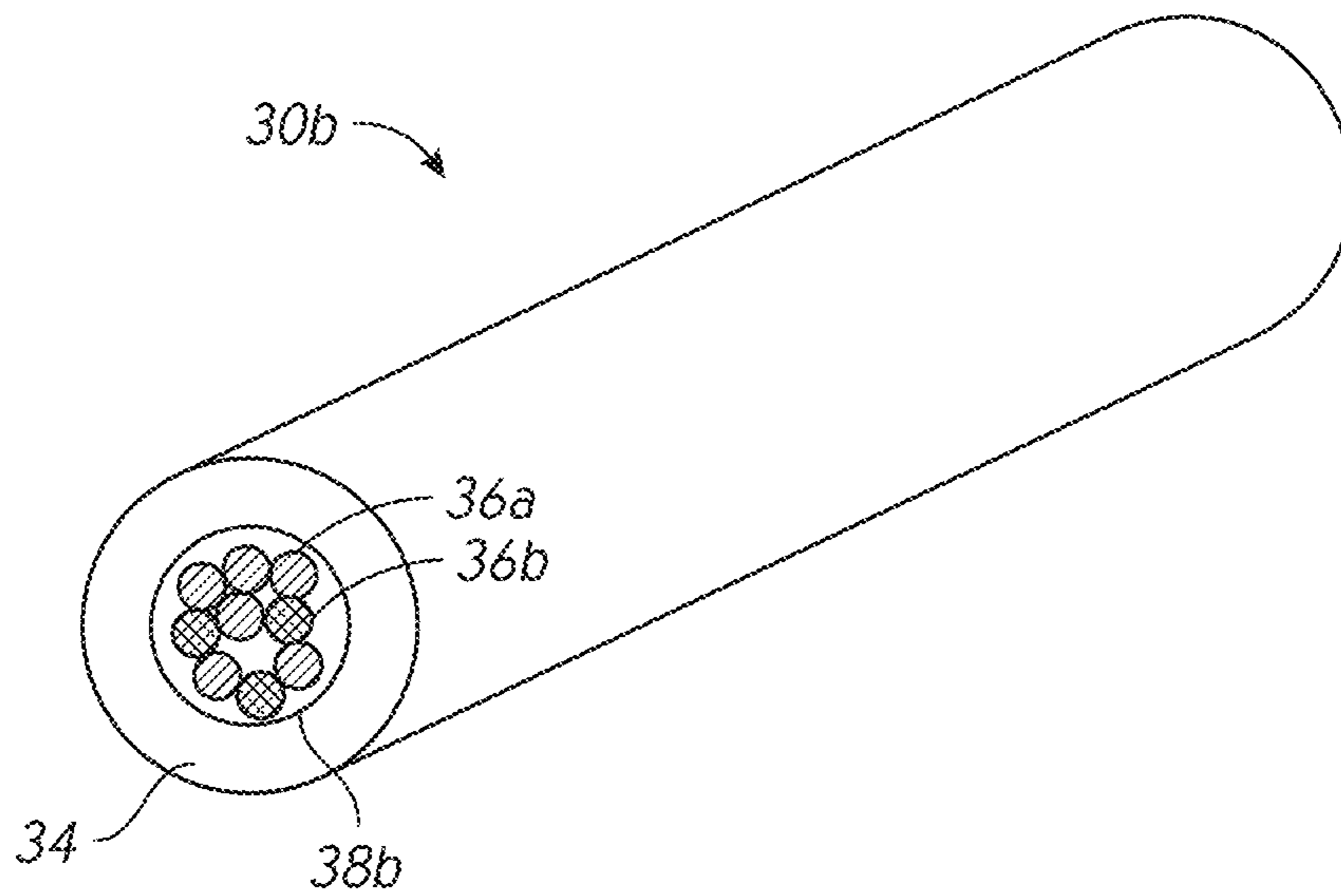


FIG. 3B

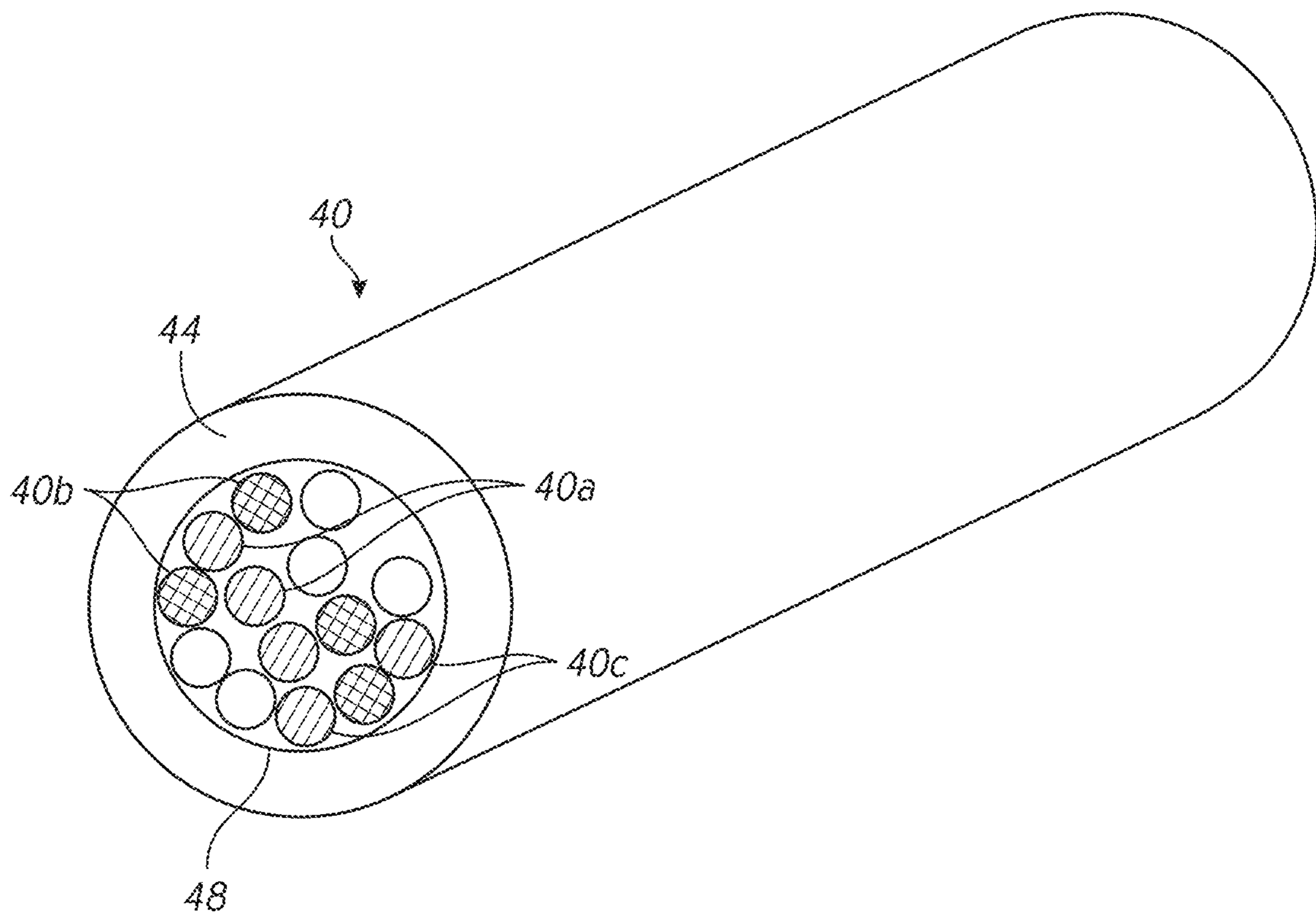


FIG. 4

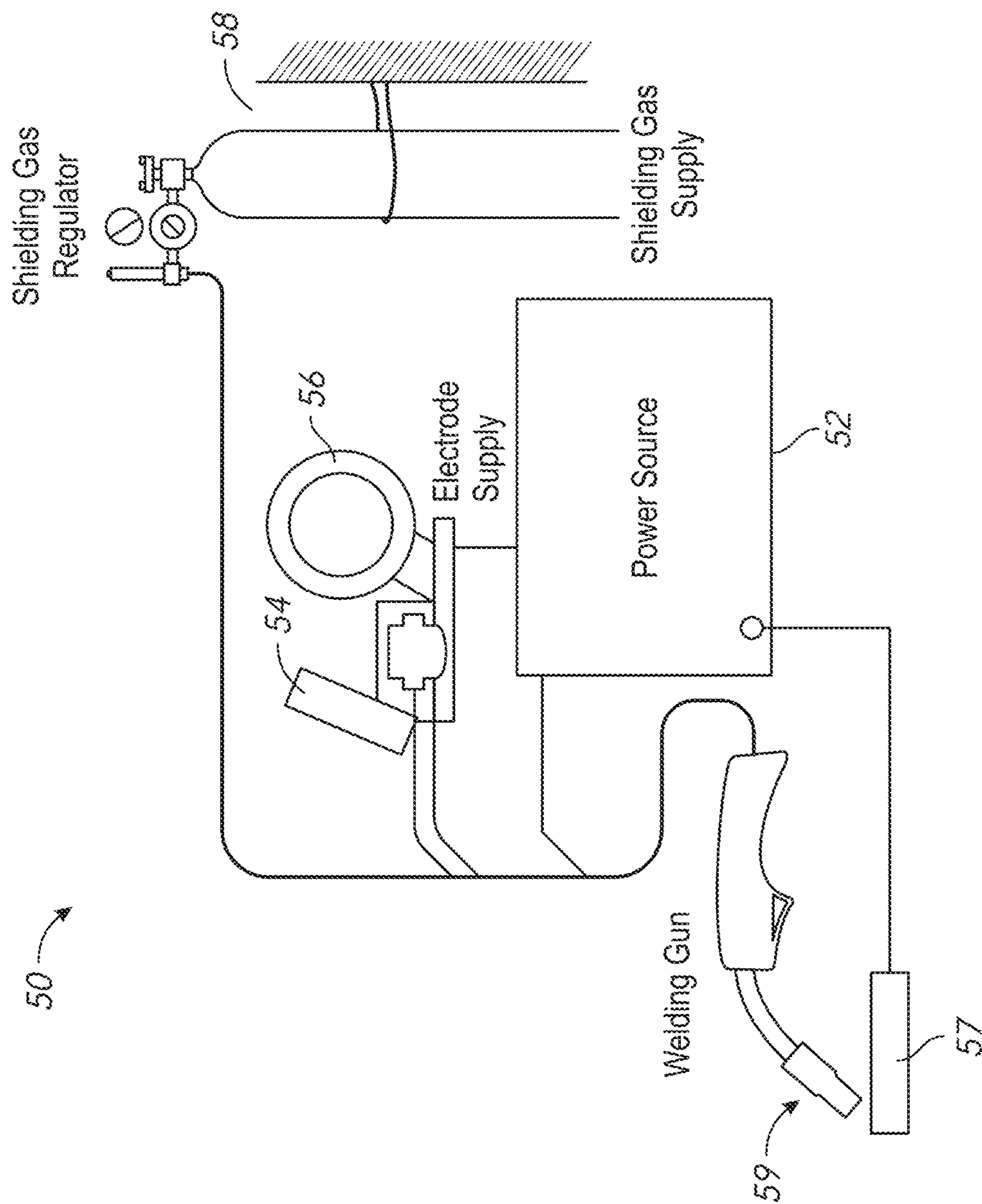


FIG. 5

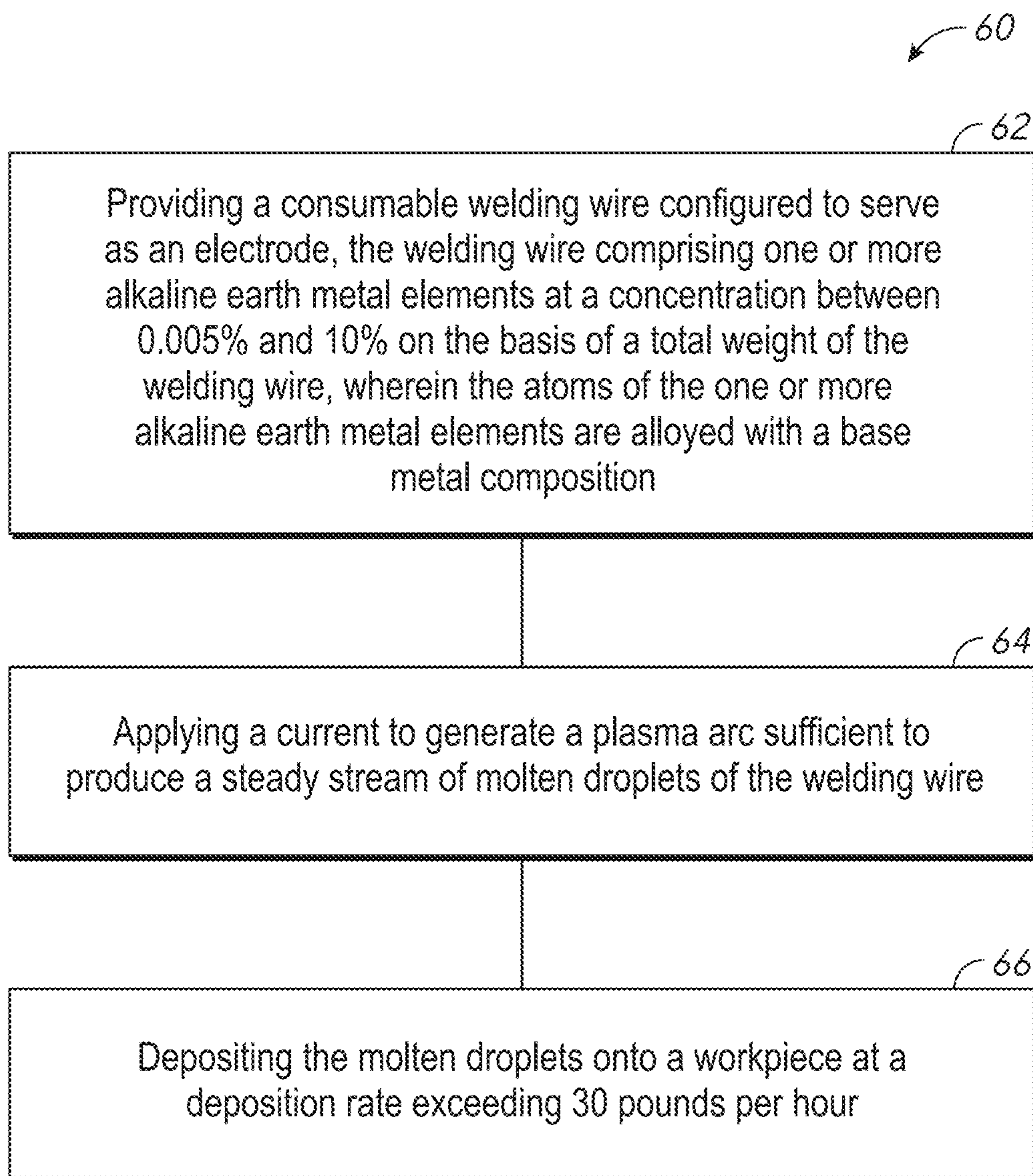


FIG. 6

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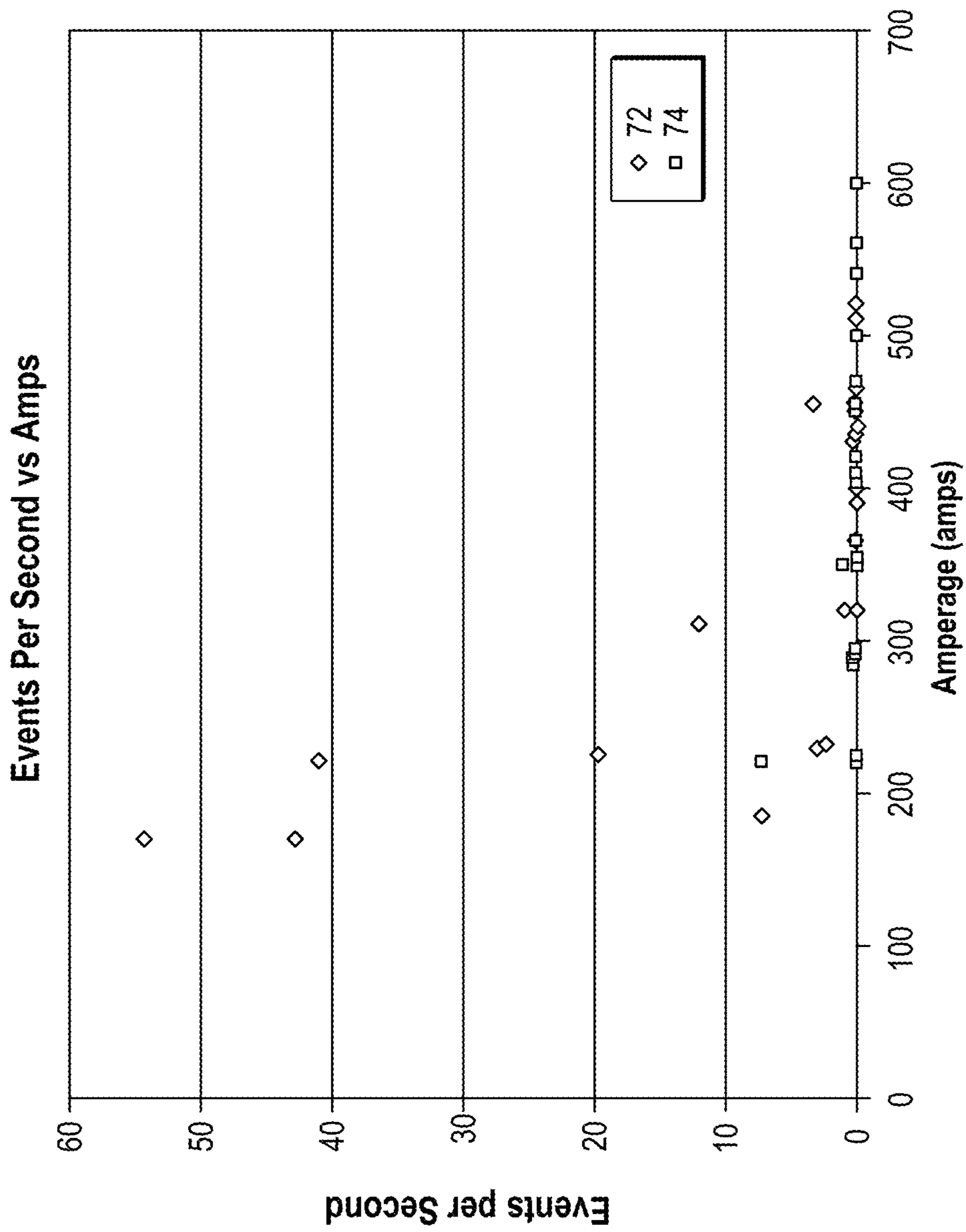


FIG. 7

810



820

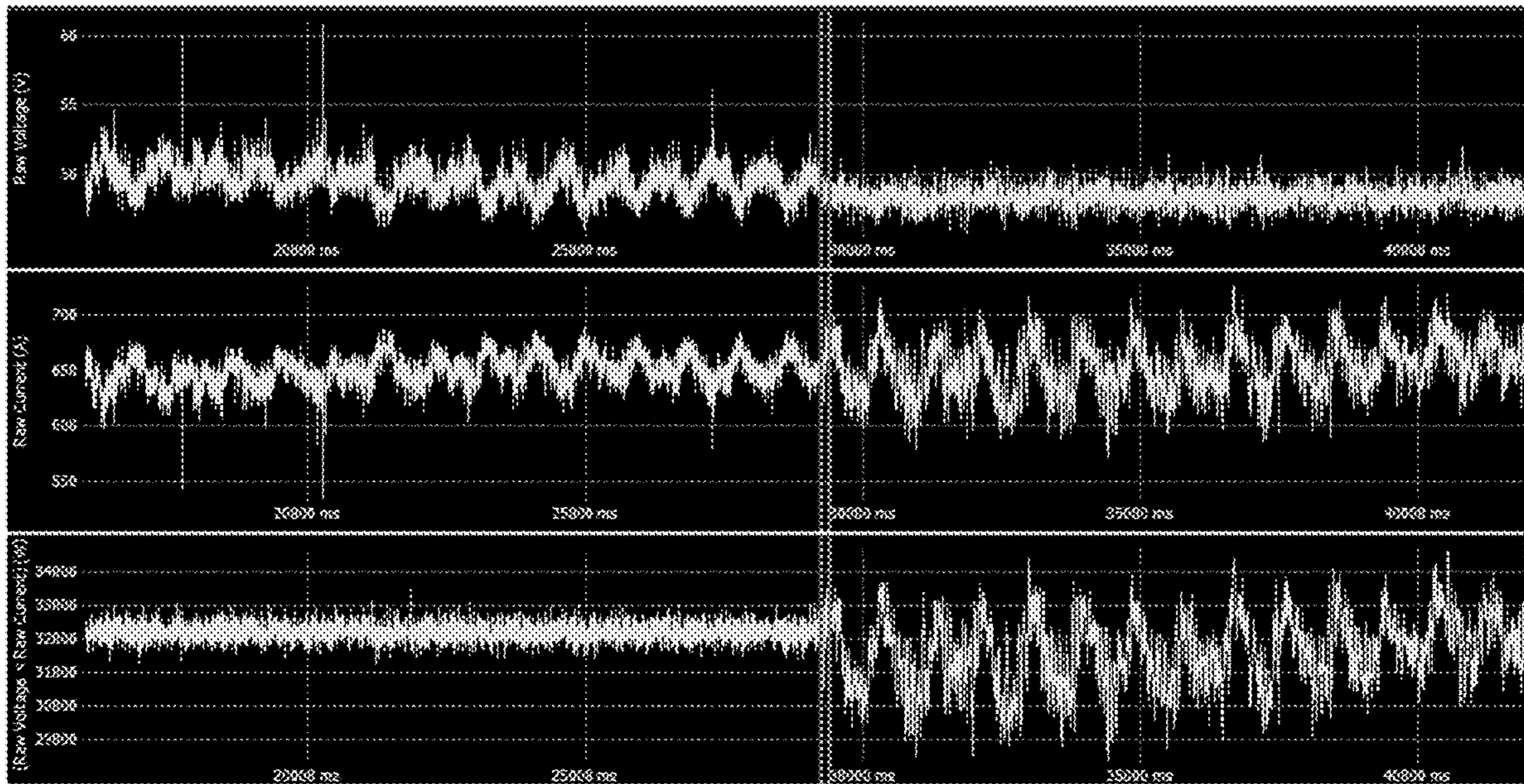
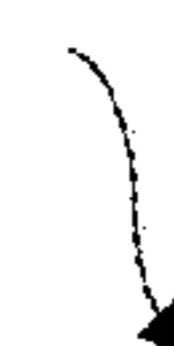


FIG. 8

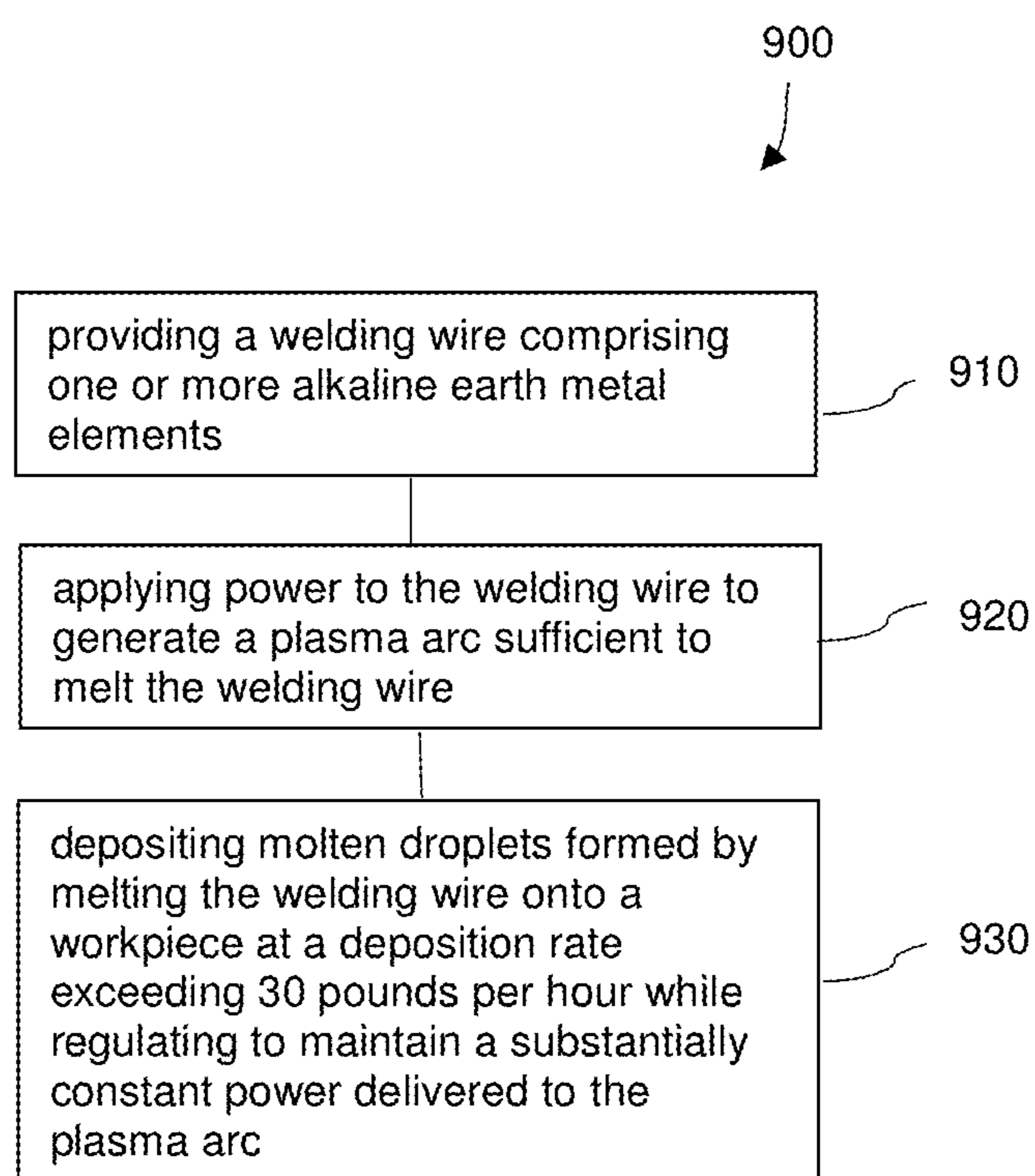


FIG. 9

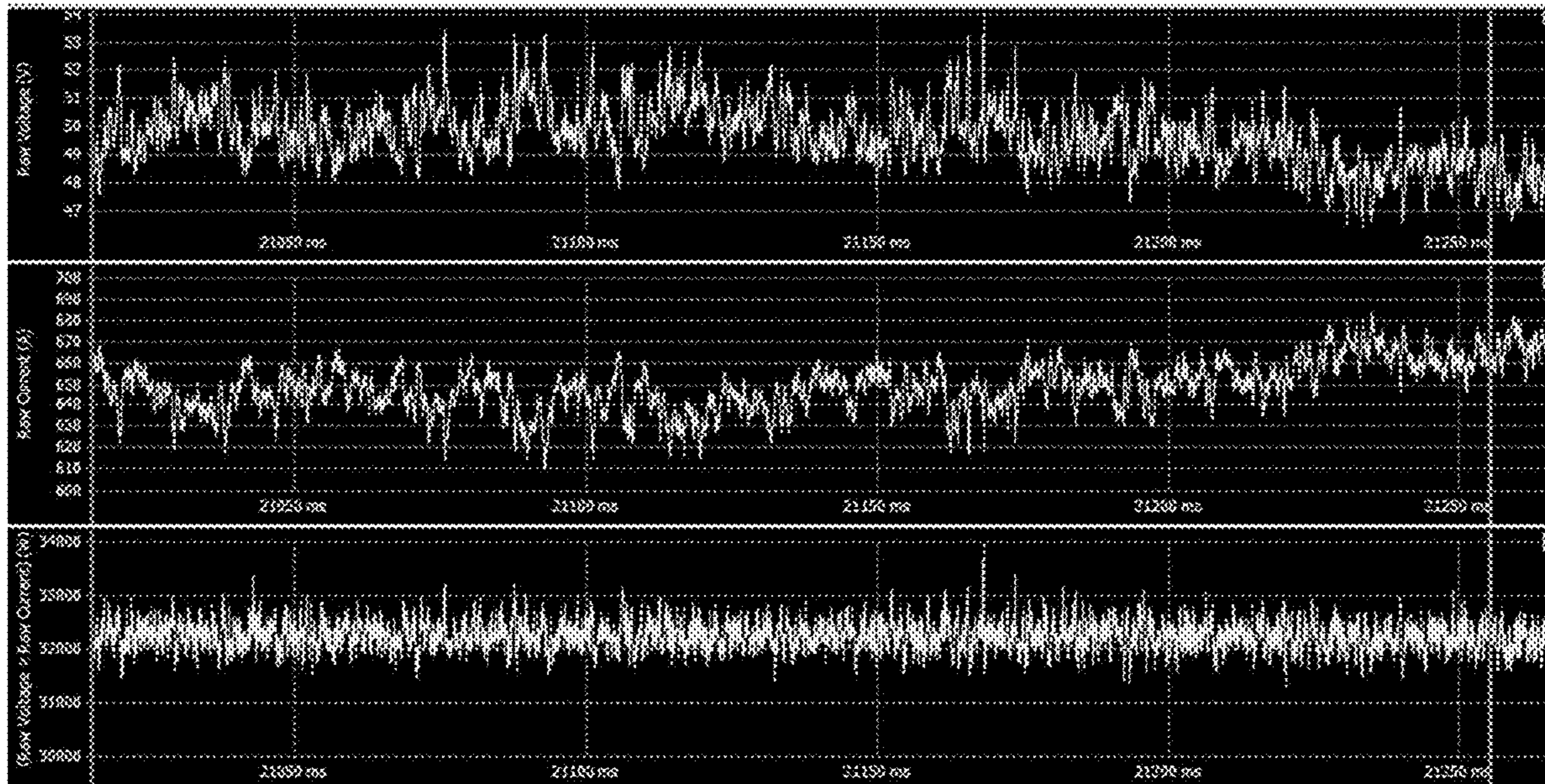


FIG. 10A

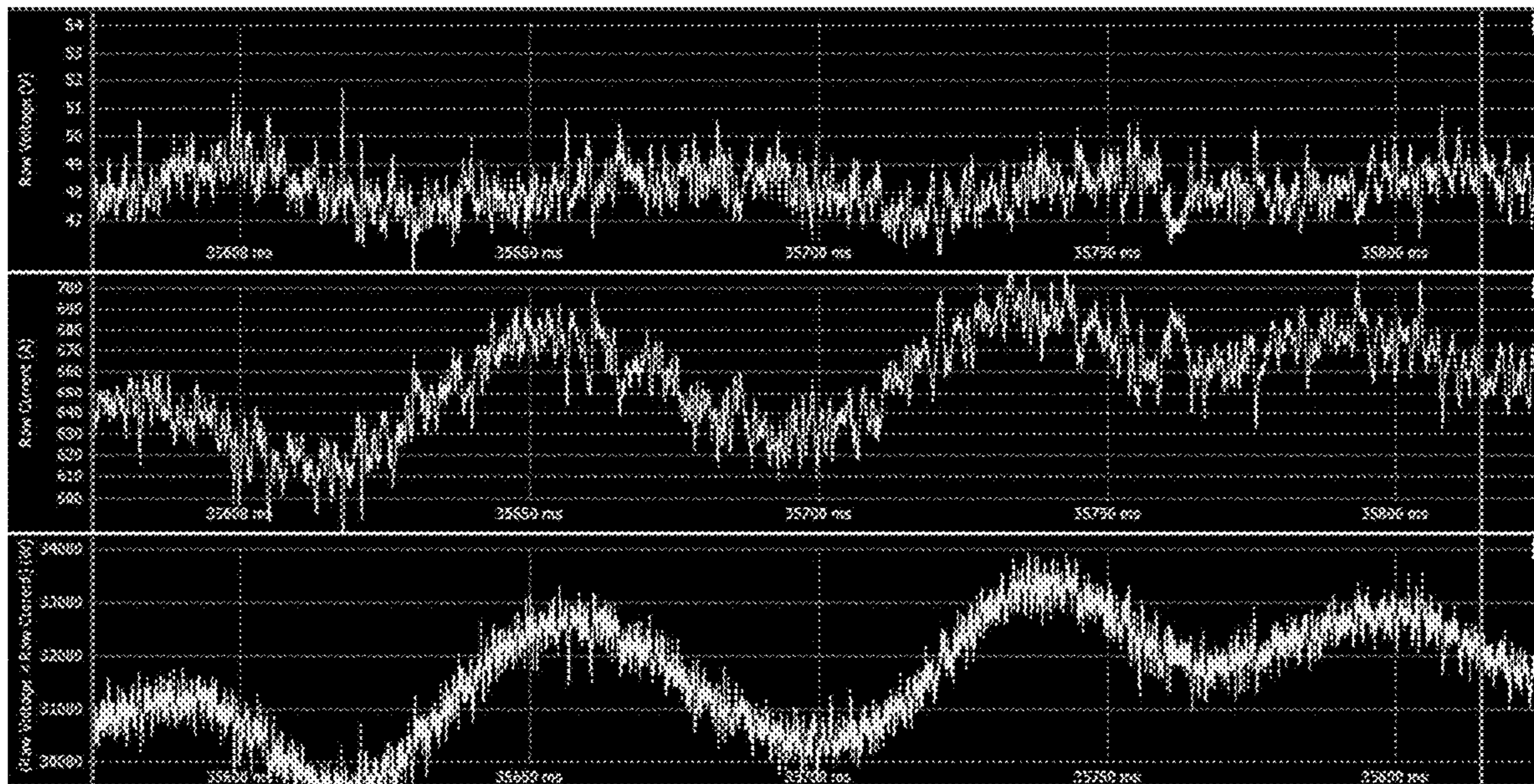


FIG. 10B

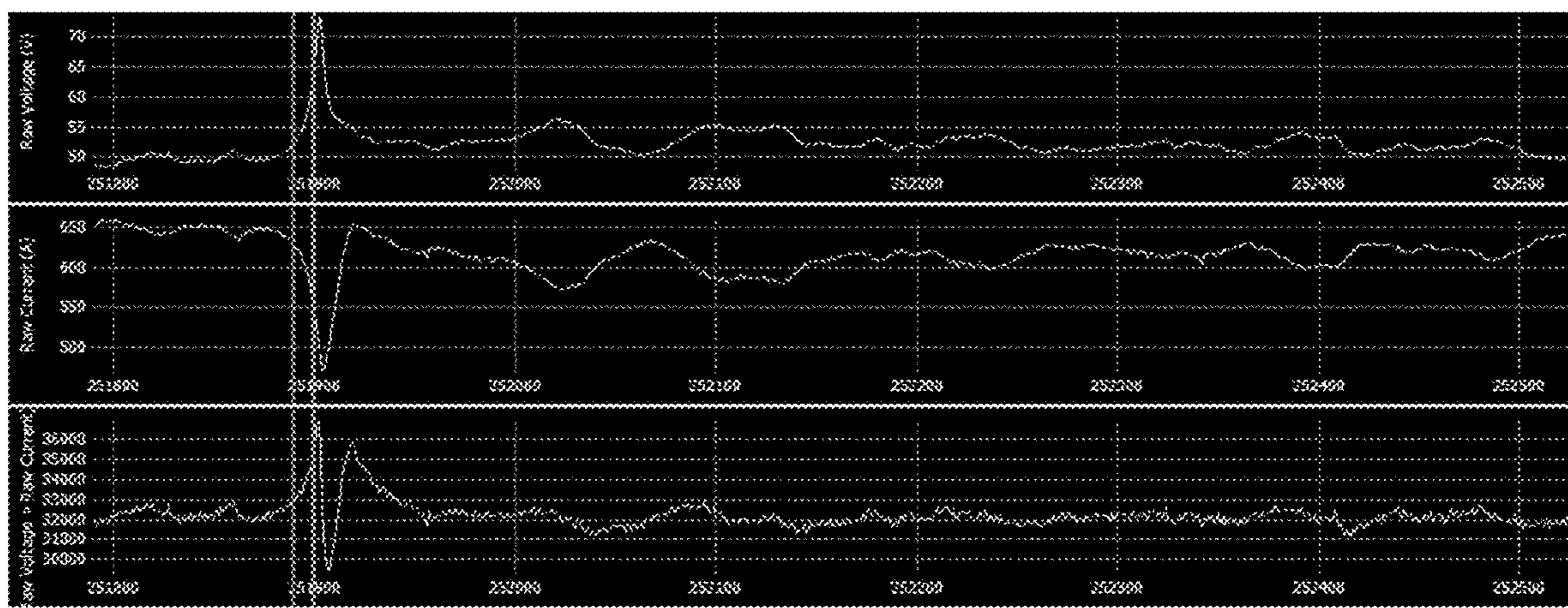


FIG. 11A

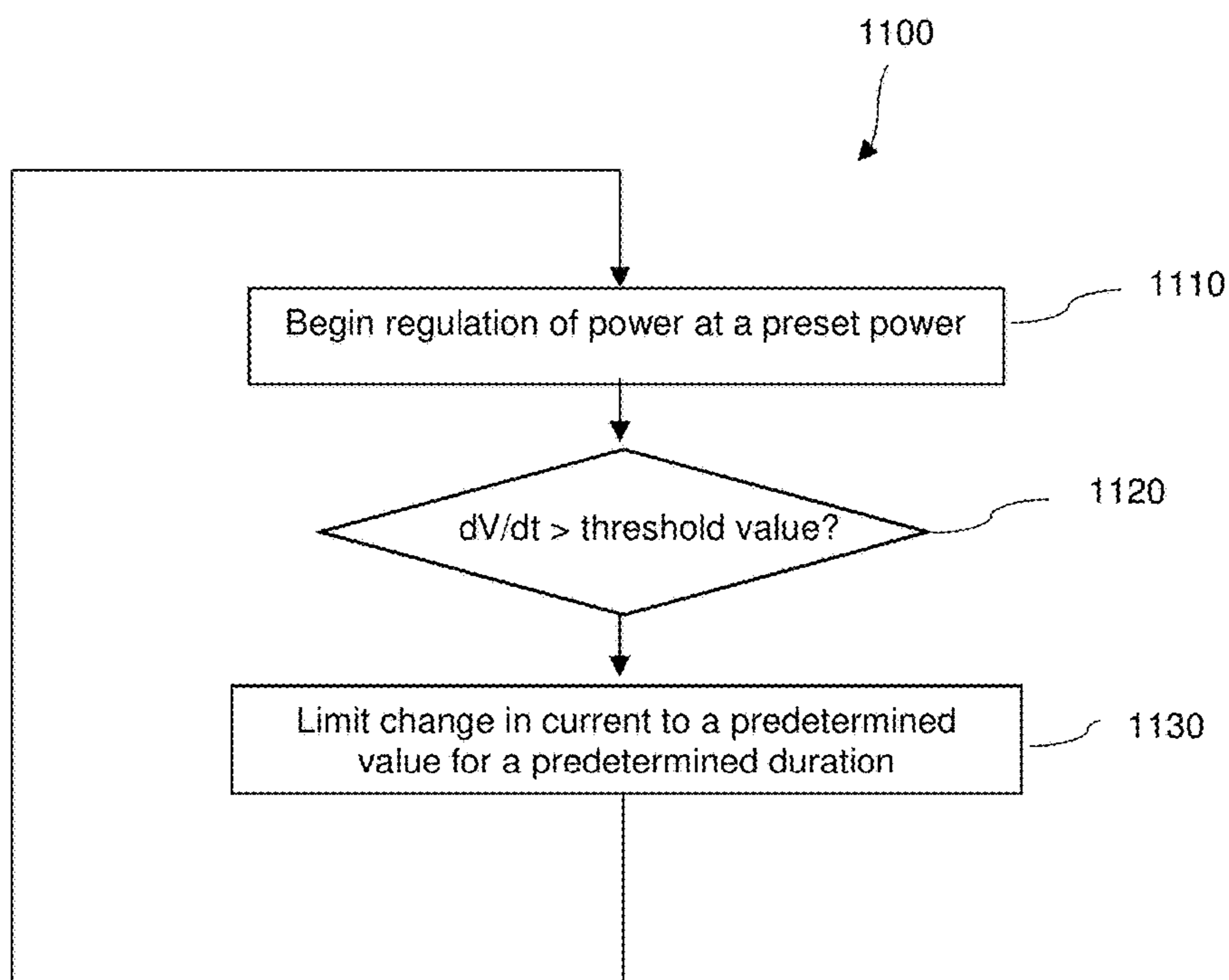


FIG. 11B

1

WELDING ELECTRODE WIRES HAVING ALKALINE EARTH METALS

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. patent application Ser. No. 15/353,520, filed Nov. 16, 2016, entitled "WELDING ELECTRODE WIRES HAVING ALKALINE EARTH METALS," the content of which is incorporated herein by reference in its entirety.

BACKGROUND

Technological Field

The disclosed technology generally relates to welding, and more particularly to consumable electrode wires for metal arc welding.

Description of the Related Art

In metal arc welding technologies, an electric arc is created between a consumable weld electrode wire, which serves as one electrode that advances towards a workpiece, which serves as another electrode. The arc melts a tip of the metal wire, thereby producing droplets of the molten metal wire that deposit onto the workpiece forms a weld bead.

As the complexity of welding requirements continues to grow, various technological approaches to address the increasingly complex requirements are being proposed. For example, competing demands include achieving high deposition rates for productivity, while simultaneously achieving a high quality weld bead in appearance and in mechanical properties, such as high yield strength, ductility and fracture toughness.

In particular, heavy fab users often desire very high deposition rates, e.g. deposition rates of ~30 lbs/hr or higher for open-arc welding. Some welding technologies aim to address this and other requirements by improving the consumables, e.g. by improving the physical designs and compositions of the electrode wires. However, in prior art electrodes, deposition at such high deposition rate often result in instability of the plasma arc, which in turn results in unacceptable quality of the weld bead. Thus, there is a need for consumable weld electrode wires capable of being used at high deposition rates while producing high quality weld.

SUMMARY

In one aspect, a consumable welding wire, e.g., a metal-cored consumable welding wire, configured to serve as an electrode during welding includes a sheath having a first base metal composition. The welding wire additionally includes a core surrounded by the sheath and comprising particles having a second base metal composition intermixed with one or more alkaline earth metal elements at a concentration between 0.005% and 10% on the basis of a total weight of the welding wire.

In another aspect, a method of metal arc welding comprises providing a consumable welding wire, e.g., a metal-cored consumable welding wire, configured to serve as an electrode, the welding wire comprising one or more alkaline earth metal elements at a concentration between 0.005% and 10% on the basis of a total weight of the metal-core wire, where the atoms of the one or more alkaline earth metal

2

elements are alloyed with a base metal composition. The method additionally includes applying a current to generate a plasma arc sufficient to produce a steady stream of molten droplets formed of the material of the welding wire, thereby depositing the molten droplets onto a workpiece at a deposition rate exceeding 30 pounds per hour.

In another aspect, a system for metal arc welding includes a consumable welding wire, e.g., a metal-cored consumable welding wire, configured to serve as an electrode, where the welding wire comprises one or more alkaline earth metal elements at a concentration between 0.005% and 10% on the basis of a total weight of the welding wire, and where the atoms of the one or more alkaline earth metal elements are alloyed with a base metal composition. The system additionally includes a power source configured to apply a current to generate a plasma arc sufficient to produce a steady stream of molten droplets formed of the material of the welding wire. The system further includes a weld gun configured to deposit the molten droplets onto a workpiece at a deposition rate exceeding 30 pounds per hour.

In another aspect, a method of arc welding includes providing a welding wire comprising one or more alkaline earth metal elements. The method additionally includes applying power to the welding wire to generate a plasma arc sufficient to melt the welding wire. The method additionally includes depositing molten droplets formed by melting the welding wire onto a workpiece at a deposition rate exceeding 30 pounds per hour while regulating to maintain a substantially constant power delivered to the plasma arc.

In another aspect, a method of arc welding includes applying power to a welding wire to generate a plasma arc sufficient to melt the welding wire. The method additionally includes depositing molten droplets formed by melting the welding wire onto a workpiece at a deposition rate exceeding 30 pounds per hour. Depositing is performed while regulating power delivered to the plasma arc such that a standard deviation of the power delivered to the plasma arc is less than 2% of an average power delivered to the plasma arc.

In another aspect, a method of arc welding includes applying power to a welding wire to generate a plasma arc sufficient to melt the welding wire. The method additionally includes depositing molten droplets formed by melting the welding wire onto a workpiece at a deposition rate exceeding 30 pounds per hour, wherein depositing is performed while regulating power delivered to the plasma arc. Regulating power comprises limiting an amount of change in current.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic illustration of a configuration of electrodes in a metal arc welding process.

FIG. 2A is schematic illustration of an electrode wire comprising one or more alkaline earth metal elements, according to embodiments.

FIG. 2B is a schematic illustration of a weld bead formation using an electrode wire comprising one or more alkaline earth metal elements, according to embodiments.

FIG. 2C is a schematic illustration of a concentration profile of the one or more alkaline earth metal elements along a weld centerline AA' of FIG. 2B.

FIG. 3A is a schematic illustration of a metal-cored electrode wire having a core comprising one or more alkaline earth metal elements, according to embodiments.

FIG. 3B is a schematic illustration of a metal-cored electrode wire having a core comprising one or more alkaline earth metal elements, according to embodiments.

FIG. 4 is a schematic illustration of a metal-cored electrode wire having a core comprising one or more alkaline earth metal elements and fluorine-containing particles, according to embodiments.

FIG. 5 is a schematic illustration of a metal arc welding system configured for high deposition rate using an electrode wire comprising one or more alkaline earth metal elements, according to embodiments.

FIG. 6 is a flow chart of a method of metal arc welding using an electrode wire comprising one or more alkaline earth metal elements, according to embodiments.

FIG. 7 is a graph illustrating experimental arc instability monitoring result of an electrode wire comprising one or more alkaline earth metal elements, according to embodiments.

FIG. 8 illustrates a comparison of experimental waveforms generated during power-regulated arc welding according to embodiments and during a constant voltage arc welding.

FIG. 9 illustrates a method of power-regulated arc welding, according to various embodiments.

FIG. 10A illustrates experimental waveforms generated during power-regulated arc welding according to embodiments.

FIG. 10B illustrate a comparative experimental waveforms generated during a constant voltage arc welding.

FIG. 11A illustrates experimental waveforms generated during power-regulated arc welding, according to embodiments.

FIG. 11B illustrates an example method of power-regulated arc welding including limiting an amount of change in current, according to embodiments.

DETAILED DESCRIPTION

FIG. 1 is a schematic illustration of a configuration of electrodes in a metal arc welding process. In metal arc welding, e.g., gas-metal arc welding (GMAW), an electric arc is created between a consumable metal wire 6, which is electrically connected to one electrode 4 (e.g., anode (+)), and a workpiece 2, which serves as another electrode (e.g., cathode (-)). Thereafter, a plasma 8 is sustained, which contains neutral and ionized gas molecules, as well as neutral and charged clusters or droplets of the material of the metal wire 6 that have been vaporized by the arc. The consumable metal wire 6 advances towards the work piece 2, and the molten droplets of the metal wire 6 deposits onto the workpiece, thereby forming a weld bead.

Widely used arc welding processes include gas-metal arc welding processes, which can employ either solid electrode wires (GMAW) or metal-cored wires (GMAW-C), flux-cored arc welding processes (FCAW), which can be gas shielded flux-cored arc welding (FCAW-G) or self-shielded flux-cored arc welding (FCAW-S), shielded metal arc welding (SMAW) and submerged arc welding (SAW), among others.

As described herein, metal cored electrodes (GMAW-C) refer to electrodes having a core whose ingredients are primarily metallic. When present, nonmetallic components in the core have a combined concentration less than 5%, 3% or 1% on the basis of the total weight of each electrode. The GMAW-C electrodes are characterized by a spray arc and excellent bead capabilities.

In gas-metal arc welding using solid (GMAW) or metal-cored electrodes (GMAW-C), a shielding gas is used to provide protection for the weld pool and the weld bead against atmospheric contamination during welding. When solid electrodes are used, they are appropriately alloyed with active ingredients that, in combination with the shielding gas, are designed to provide porosity-free welds with the desired physical and mechanical properties of the resulting weld bead. When metal-cored electrodes are used, some of the active ingredients are added in the core of a metallic outer sheath, and designed to provide a similar function as in the case of solid electrodes.

Solid and metal-cored electrodes are designed to provide, under appropriate gas shielding, a solid, substantially porosity free weld with yield strength, tensile strength, ductility and impact strength to perform satisfactorily in the final applications. These electrodes are also designed to minimize the quantity of slag generated during welding. For some applications, metal-cored electrodes can be used as an alternative to solid wires to increase productivity. The metal-cored electrodes are composite electrodes having a core that is at least partially filled and surrounded by a metallic outer sheath. The core can include metal powder and active ingredients to help with arc stability, weld wetting and appearance and desired physical and mechanical properties. The metal-cored electrodes are manufactured by mixing the ingredients of the core material and depositing them inside a formed strip, and then closing and drawing the strip to the final diameter. For some applications, cored electrodes can provide increased deposition rates and a wider, more consistent weld penetration profile compared to solid electrodes. Moreover, for some applications, cored electrodes can provide improved arc action, generate less fume and spatter, and provide weld deposits with better wetting compared to solid electrodes.

In flux-cored arc welding (FCAW, FCAW-S, FCAW-G), cored electrodes are used. Cored electrodes used in flux-cored arc welding have a core that is at least partially filled and surrounded by a metallic outer sheath, similar to metal-cored electrodes described above. However, cored electrodes used in flux-cored arc welding additionally includes fluxing agents designed to provide protection for the weld pool and the weld bead against atmospheric contamination during welding, at least partially in lieu of a shielding gas. The cored electrodes used in flux-cored arc can additionally include other active ingredients to help with arc stability, weld wetting and appearance and desired physical and mechanical properties. A large number of compositions of the fluxing agent have been developed to control the arc stability, modify the weld metal composition, and to provide protection from atmospheric contamination. Arc stability is commonly controlled by modifying the composition of the flux. It is therefore often desirable to have substances which function well as plasma charge carriers in the flux mixture. In some applications, fluxes can also modify the weld metal composition by rendering impurities in the metal more easily fusible and providing substances with which these impurities may combine. Other materials are sometimes added to lower the slag melting point, to improve slag fluidity, and to serve as binders for the flux particles.

Various embodiments disclosed herein aim to address the increasingly complex requirements of high deposition rate in various welding processes described above. Advantageously, embodiments disclosed herein relate to electrodes comprising relatively large amounts of alkaline earth metal elements. In some embodiments, the electrodes are solid electrodes containing the relatively large amounts of alka-

line earth metal elements. In some other embodiments, the electrodes are cored electrodes, e.g., metal-cored electrodes or flux-cored electrodes, for providing a broad range of metallurgical and physical characteristics that may be difficult or impossible to achieve with traditional stick welding. As described herein, high deposition rate refer to a deposition rate exceeding about 30 lbs/hr, which is much higher than rates practically achievable with most open arc welding processes. Embodiments of electrodes disclosed herein allow for such high deposition rates without developing excessive electrical resistance heating, even with relatively small diameter electrodes. In addition, resulting weld beads have desirable mechanical properties, such as yield strengths exceeding 80,000 psi.

Welding Wires Comprising Alkaline Earth Metal Elements

FIG. 2A is schematic illustration of a welding electrode wire **20**, e.g., a metal cored welding electrode wire, comprising a base metal composition and one or more alkaline earth metal elements (Be, Mg, Ca, Sr, Ba, Ra), according to embodiments.

In various embodiments described herein including the illustrated embodiment of FIG. 2A, the base metal composition comprises a steel composition or an aluminum composition. In some embodiments, the base metal composition can be a carbon steel composition. To provide some non-limiting example compositions, a carbon steel composition includes Fe and one or more of C at a concentration between about 0.01 wt % and about 0.5 wt %, Si at a concentration between about 0.1 wt % and about 1.5 wt %, Mn at a concentration between about 0.5 wt % and about 5 wt %, S at a concentration between about 0.001 wt % and about 0.05 wt %, P at a concentration between about 0.001 wt % and about 0.05 wt %, Ti at a concentration between about 0.01 wt % and about 0.5 wt %, Zr at a concentration between about 0.01 wt % and about 0.5 wt %, Al at a concentration between about 0.01 wt % and about 0.5 wt % and Cu at a concentration between about 0.1 wt % and about 1 wt %.

In some other embodiments, the base metal composition can be a low-carbon steel composition. Some non-limiting examples include compositions having C at a concentration less than about 0.10 wt % and Mn at a concentration up to about 0.4 wt %, and compositions having C at a concentration less than about 0.30 wt % and Mn at a concentration up to about 1.5 wt %.

In some other embodiments, the base metal composition can be a low-alloy steel composition. To provide some non-limiting example compositions, a low-alloy steel composition includes Fe and one or more of C at a concentration between about 0.01 wt % and about 0.5 wt %, Si at a concentration between about 0.1 wt % and about 1.0 wt %, Mn at a concentration between about 0.5 wt % and about 5 wt %, S at a concentration between about 0.001 wt % and about 0.05 wt %, P at a concentration between about 0.001 wt % and about 0.05 wt %, Ni at a concentration between about 0.01 wt % and about 5 wt %, Cr at a concentration between about 0.1 wt % and about 0.5 wt %, Mo at a concentration between about 0.1 wt % and about 1 wt %, V at a concentration between about 0.001 wt % and about 0.1 wt %, Ti at a concentration between about 0.01 wt % and about 0.5 wt %, Zr at a concentration between about 0.01 wt % and about 0.5 wt %, Al at a concentration between about 0.01 wt % and about 0.5 wt % and Cu at a concentration between about 0.1 wt % and about 1 wt %.

In some other embodiments, the base metal composition can be a stainless steel composition. To provide some non-limiting example compositions, a stainless steel composition typically includes Fe and one or more of C at a

concentration between about 0.01 wt % and about 1 wt %, Si at a concentration between about 0.1 wt % and about 5.0 wt %, Cr at a concentration between about 10 wt % and about 30 wt %, Ni at a concentration between about 0.1 wt % and about 40 wt %, Mn at a concentration between about 0.1 wt % and about 10 wt %, S at a concentration between about 0.001 wt % and about 0.05 wt % and P at a concentration between about 0.001 wt % and about 0.05 wt %.

Without being bound to any theory, each element discussed above can provide particular advantages in steel welding. Carbon can provide strength and ductility in the weldment. Manganese is another element that can add strength to the weld and can also serve as a deoxidizer which removes oxygen from the weld and reduces weld metal porosity. Silicon can serve as a deoxidizer, removing oxygen from the weld, and reduce the chance of weld metal porosity. In general, the higher the level of silicon in the metal, the more fluid the weld puddle. Additions of silicon can also increase tensile and yield strength. Phosphorus is generally undesirable to the weld deposit, as it can contribute to weld cracking. Sulfur is also generally undesirable for weldability and can contribute to weld cracking. However, in limited amounts, sulfur or phosphorus can improve fluidity and wetting of the weld puddle. Copper can be present as a result of coating of the wire electrodes (if copper-coated) for improved conductivity, and therefore, better arc initiation. Titanium can serve as a deoxidizer, in addition to silicon and manganese. Some deoxidizers aid in removing both oxygen and nitrogen from the weld, thereby reducing the occurrence of weld metal porosity. Zirconium, Aluminum, and Nickel can serve as deoxidizers. Molybdenum can add strength and improve impact properties, even when the weld is subject to stress relieving post-weld heat treatment. Chromium can improve corrosion resistance.

Base metal compositions other than steel compositions are possible. In some embodiments, the base metal composition can be an aluminum composition. To provide some non-limiting example compositions, an aluminum composition includes Al and one or more of Mn at a concentration between about 0.01 wt % and about 5%, Si at a concentration between about 0.1 wt % and 20 wt %, Fe at a concentration between about 0.1 wt % and about 1.0 wt %, Mg at a concentration between about 0.01 wt % and about 10 wt %, Cr at a concentration between about 0.01 wt % and about 1.0 wt %, Cu at a concentration between about 0.01 wt % and 10 wt %, Ti at a concentration between about 0.01 wt % and about 1.0 wt % and Zn at a concentration between about 0.01 wt % and about 1.0 wt %. These and other aluminum compositions can be included as part of the base metal of the welding electrode wire **20**, according to embodiments.

In various embodiments described herein including the illustrated embodiment of FIG. 2A, the one or more alkaline earth metal elements (Be, Mg, Ca, Sr, Ba, Ra) are present at a concentration range between a minimum concentration of about 0.005%, 0.050% or 0.1%, and a maximum concentration of about 0.5%, 5% or 10%, on the basis of the total weight of the electrode wire.

When more than one alkaline earth metal elements are present, the above-indicated concentrations represent a combined concentration or an individual concentration.

In one particular embodiment, Ba is present at a concentration between about 0.05% and 5% or between about 0.1% and about 10%, for instance about 0.12%.

In another embodiment, Ca is present at a concentration between about 0.05% and 5% or between about 0.1% and about 10%, for instance about 0.12%.

In yet another embodiment, Ba and Ca are both present each at a concentration between about 0.05% and 5% or between about 0.1% and about 10%, for instance about 0.12%.

In some embodiments, the atoms of the alkaline earth metal are alloyed with the base metal composition. That is, the atoms of the alkaline earth metal form metallic bonds with atoms of the base metal composition. In some other embodiments, the atoms of alkaline earth metal are clustered, e.g., in the form of precipitates, within a matrix of the base metal composition. Yet other embodiments are possible, where the alkaline earth metal element is in the form of a compound, e.g., silicates, titanates, carbonates, halides, phosphates, sulfides, hydroxides, fluorides and oxides that form a mixture with the base metal composition.

Inventors have found that having the alkaline earth metal at concentrations described herein can provide, among other advantages, of providing stability to the arc at high current (e.g., exceeding 200 amps or exceeding 400 amps) for achieving high deposition rates (e.g., exceeding 30 lbs/hr). In addition, under some circumstances, the alkaline earth metal at concentrations described herein can advantageously serve as a deoxidizer.

According to embodiments, the above-described features can be achieved at least in part by configuring the weld metal electrodes **20** to have a diameter range of 0.045"-3/32" (1.1 mm-2.4 mm)

In the following, with respect to FIGS. **2B** and **2C**, without being bound to any theory, evolution of alkaline earth metal elements is described as a weld bead is formed, when welding electrode wires according to embodiments are used. It will be appreciated that the following description is applicable to welding electrode wires described above with respect to FIG. **2A**, as well as embodiments described infra, with respect to FIGS. **3A-3B** and **4**. Furthermore, while the description applies to steel base metal compositions, analogous concepts apply to aluminum base metal compositions.

According to the equilibrium phase diagram (not shown) of the Fe-C system, several phases of iron exist, including the body-centered cubic ferrite (also known as α -Fe), which is stable below about 910° C., the face-centered cubic austenite (also known as γ -Fe), which is stable above about 730° C., and delta-ferrite (δ -Fe), which is stable above about 1,390° C. and up to the melting point at about 1,539° C. During welding, depending on the base steel composition, the liquefied electrode composition can be quenched via a number of pathways to form a solid weld bead. For example, for carbon steel and low-alloy steel compositions, the pathway can include $L \rightarrow \delta + L$, followed by $\delta + L \rightarrow \delta + \gamma + L$, followed by $\delta + \gamma + L \rightarrow \gamma + \delta + L\gamma$. Alternatively, the pathway for carbon steel and low-carbon steel compositions can include $L \rightarrow \delta + L$, followed by $\delta + L \rightarrow \delta$ for a peritectic composition. For a stainless steel composition, the pathway can be $L \rightarrow \delta + L$, followed by $\delta + L \rightarrow \delta + \gamma$. At concentrations of the alkaline earth metal described above, when the liquefied weld metal electrode, which includes dissolved alkaline earth metal elements, solidifies into a weld bead following one of the pathways described above, a relatively small amount of atoms of the alkaline earth metal element become incorporated into the lattice (e.g., a body-centered cubic lattice or a face-centered cubic lattice of the steel composition) of the steel composition substitutionally and/or interstitially. As a result, most of the alkaline earth metal atoms segregate or precipitate out to become incorporated into the resulting slag, according to embodiments. As a result, because most of the alkaline earth metal atoms do not substantially get

incorporated into the resulting beads, the resulting weld beads are relatively free of the alkaline earth metal atoms.

FIG. **2B** is a schematic illustration of a weld bead formation **22** using an electrode wire comprising one or more alkaline earth metal elements, according to embodiments. In FIG. **2B**, weld metal crystals **24** of a weld bead have crystallized from a liquid phase of the electrode weld metal in a previous weld puddle, such as the weld puddle **28**. The weld puddle **28** represents a liquid phase of the electrode weld metal as the weld bead continues to form in the x-direction. The weld bead formation **22** represents a bead formation under relatively high deposition rates, e.g., when the deposition rate exceeds ~30 lbs/hr. Under such circumstances, the shape of the weld puddle **28** can become elongated (e.g., length (l)/width (w) > 1.5) in the direction along the weld centerline AA', in the form of a pear shape.

According to embodiments, when the concentration of alkaline earth metal elements is relatively high, e.g., higher than the solubility limit, as the weld puddle solidifies into one or more solid phases of the steel or aluminum compositions, impurity atoms may segregate to the liquid/solid interface **26** or to the surface of the bead as the weld bead grows, e.g., when the amount of alkaline earth metal atoms exceeds the amount that can be accommodated by the grains and the grain boundaries of the weld metal crystals **24**. In addition, the weld pool **28** can continue to become enriched in concentration of the alkaline earth metal elements, eventually resulting in a slag which contains the segregated alkaline earth metal elements.

FIG. **2C** shows a graph **29** schematically illustrating a concentration profile of the one or more alkaline earth metal elements along a weld centerline AA' of FIG. **2B**. According to some embodiments, the concentration of the alkaline earth metal element is selected such that a substantial amount, e.g., essentially all, of the alkaline earth metal atoms are segregated from the grains and/or grain boundaries of the weld metal crystals **24**, which can include γ -Fe and/or δ -Fe grains, for embodiments in which the base metal composition is a steel composition, as illustrated in FIG. **2C**. The graph **29** illustrates the concentration of alkaline earth metal in the weld centerline direction (x-direction) along a cross section of the weld centerline AA' of FIG. **2B**. As illustrated in FIG. **2C**, in some embodiments, the concentration **29a** of a relatively small amount, e.g., a trace amount, of the alkaline earth metal which gets incorporated in the solid weld bead at or below the solubility limit, is relatively constant at C_S along the x-direction. In addition, substantially all of the alkaline earth metal segregates at the liquid/solid interface **26** and/or to the surface such that the concentration **29b** of the alkaline earth metal at C_L in the weld puddle **28** substantially exceeds that of C_S . The weld puddle **28** can continue to become enriched in concentration of the alkaline earth metal elements, eventually resulting in a slag.

When the weld puddle, which becomes enriched with the ala is cooled to form a weld bead, virtually all of alkaline earth metal segregates to the surface of the weld bead, e.g., as part of a slag. In various embodiments, advantageously, greater than about 80%, greater than about 90% or greater than about 99% of the initial concentration of the alkaline earth metal in the electrode wire segregates to the surface of the bead and/or the liquid/solid interface, thereby forming a slag which can be easily removed.

Various technical features described above with respect to FIGS. **2A-FIG. 2C** are not limited to a particular type of electrode, e.g., among solid electrode wires (GMAW), metal-cored wires (GMAW-C), flux-cored arc welding processes (FCAW), shielded flux-cored arc welding (FCAW-

G), self-shielded flux-cored arc welding (FCAW-S), shielded metal arc welding (SMAW) or submerged arc welding (SAW). In the following, particular embodiments of cored electrodes comprising alkaline earth metal elements are described in detail.

Generally, a cored electrode is a continuously fed tubular metal sheath with a core of particles or powders. The core may include fluxing elements, deoxidizing and denitrating agents, and alloying materials, as well as elements that increase toughness and strength, improve corrosion resistance, and stabilize the arc. As described above, a cored electrode can be categorized as one of the following: metal-cored electrodes (GMAW-C), self-shielded flux-cored electrodes (FCAW-S) and gas-shielded flux-cored electrodes (FCAW-G). In the embodiments described herein, it will be appreciated that particles in metal-cored electrodes that contain alkaline earth metal elements are generally metal and alloy particles, rather than compounds such as oxides or fluorides, producing only small islands of slag on the face of the weld. By contrast, flux-cored electrodes that produce an extensive slag cover during welding, which supports and shapes the bead, can have particles containing alkaline earth metal elements in the form of compounds such as oxides and fluorides. As described below, various embodiments disclosed herein can be optimized for any one of metal-cored electrodes, self-shielded flux-cored electrodes and gas-shielded flux-cored electrodes.

As described above, metal-cored electrodes are composite electrodes having a sheath formed of, e.g., a mild steel, with a core of particles having specifically selected iron and other metal powders and alloys. Additives such as stabilizers and arc enhancers can be added easily, providing a wider operating window for the welder. Metal-cored electrodes (GMAW-C) are gas-shielded types that are an alternative to solid alloy electrodes (GMAW).

Because of the flexibility in manufacturing, when a job calls for special electrodes, metal-cored electrodes can be more economical than solid electrodes. Because the manufacturing process involves blending metal powders instead of creating a special melt of steel, small quantities are easier to produce, and minimum order quantities are much lower. As a result, metal-cored electrodes can be produced with shorter turnaround times and at lower cost than special-ordered solid electrodes.

FIGS. 3A and 3B are schematic illustrations of a metal-cored electrode wire **30a/30b** having a core comprising one or more alkaline earth metal elements (Be, Mg, Ca, Sr, Ba, Ra), according to embodiments. Each of the metal-cored electrode wires **30a/30b** includes a sheath **34** comprising a first base metal composition and a core **38a/38b** surrounded by the sheath **34**. The core **38a/38b** is at least partially filled with particles comprising the one or more alkaline earth metal element(s) and a second base metal composition.

In the metal-cored electrode wires **30a/30b**, the first base metal of the sheath **34** and the second base metal of the particles in the core can include any one of the steel or aluminum compositions described above with respect to the electrode **20** of FIG. 2A. In some embodiments, the first base metal and the second base metal are the same, while in other embodiments, the first base metal and the second base metal are different. In addition, the powder component includes an alkaline earth metal in various configurations, as described below.

Referring to the metal-cored electrode **30a** of FIG. 3A, particles **32** are formed of an alloy of the second base metal composition and the alkaline earth metal, according to embodiments. Similar to the embodiment described above

with respect to FIG. 1 above, in the illustrated embodiment of FIG. 3A, atoms of alkaline earth metal element can be dissolved, or directly incorporated, in the lattice (e.g., a body-centered cubic lattice or a face-centered cubic lattice of the steel composition) of the second base metal composition, e.g., substitutionally and/or interstitially. The atoms of alkaline earth metal element can also be clustered, e.g., form precipitates, within a matrix of the second base metal composition. Alternatively embodiments are possible, where the alkaline earth metal element is in the form of a compound, e.g., silicates, titanates, carbonates, halides, phosphates, sulfides, hydroxides, fluorides and oxides.

In the illustrated embodiment of FIG. 3A, particles **32** are substantially uniform in composition and contain similar or essentially the same amount of the alkaline earth metal. Such may be the case, e.g., when the particles **32** are produced from the same or different alloy ingot.

However, referring now to the metal-cored electrode **30b** of FIG. 3B, other embodiments are possible. In the electrode **30b** of FIG. 3B, particles **36a, 36b** have different compositions. In some embodiments, particles **36a, 36b** contain different elements. In other embodiments, particles **36a, 36b** contain the same elements at different concentrations of one or more of the constituent impurities.

In some implementations, all particles **36a, 36b** include a second base metal composition (e.g., steel or aluminum composition) and one or more alkaline earth metal elements, but at different concentrations of one or both of the second base metal composition and the one or more an alkaline earth metal elements. In some other implementations, some particles **36a** include a second base metal composition while not including one or more alkaline earth metal elements, while other particles **36b** include both a second base metal composition and one or more alkaline earth metal elements. In some other implementations, some particles **36a** do not include a second base metal composition while including one or more alkaline earth metal elements, while other particles **36b** include both a second base metal composition and one or more alkaline earth metal elements. In some other implementations, some particles **36a** include a second base metal composition while including one or more alkaline earth metal, while other particles **36b** do not include a second base metal composition while including one or more alkaline earth metal. In some other implementations, some particles **36a** do not include a second base metal composition while including one or more alkaline earth metal elements, while other particles **36b** include a second base metal composition while not including one or more alkaline earth metal elements. In some other implementations, no particles include a second base metal composition while all particles **36a, 36b** include one or more alkaline earth metal elements at different concentrations.

In various embodiments described herein including the illustrated embodiment of FIGS. 3A-3B, the base metal composition comprises a steel composition or an aluminum composition having similar compositions as described above with respect to FIG. 2A.

In various embodiments described herein with respect to illustrated embodiments of FIGS. 3A-3B, one or more alkaline earth metal elements (Be, Mg, Ca, Sr, Ba, Ra) are present at concentrations described above with respect to FIG. 2A.

According to embodiments, the above-described concentrations can be achieved at least in part by configuring the metal-cored electrodes **30a/30b** to have an outer diameter (OD) between 0.045" (1.1 mm) and 0.068" (1.7 mm),

between 0.045" (1.1 mm) and 3/32" (2.4 mm) or between 0.052" (1.4 mm) and 0.068" (1.7 mm).

According to embodiments, the above-described concentrations can be achieved at least in part by configuring the contents of the core **38a/38b** and the sheath **34**, such that the contents of the core constitute, on the basis of the total weight of the metal cored electrode wires **30a/30b**, between about 1 wt % and about 80 wt %, between about 10 wt % and about 50 wt %, or between about 15 wt % and about 30 wt %.

Having the alkaline earth metal at particular concentrations and configurations described herein can have many advantages. Without subscribing to any theory, it is believed that the alkaline earth metal modifies certain plasma characteristics, e.g., increases the ionization potential. An increased ionization potential of the plasma in turn can lead to higher plasma stability at higher current, such that higher deposition rates, e.g., deposition rates exceeding 30 pounds per hour, can be sustained. In addition, as described elsewhere, because alkaline earth metal atoms do not substantially get incorporated into the resulting weld bead, degradation in mechanical properties of the resulting weldment can be prevented. Without subscribing to any theory, formation of new phases and/or excessive build-up of the alkaline earth metal in grain boundaries can be prevented.

According to some embodiments, described above with respect to metal-cored electrodes of FIGS. **3A-3B**, the metal-cored electrodes (GMAW-C) are configured for gas metal arc welding, where the shielding is provided by a shielding gas. As described above, gas metal arc welding is distinguishable from flux-cored arc welding (FCAW), in which a flux contained within the tubular electrode produces the shielding. The fluxing agent forms a slag for flux-cored arc welding (FCAW). In FCAW, the material of the flux is not intended to be incorporated into the final weld bead. Instead, the flux forms a slag, which is removed after completion of welding. Thus, in various embodiments of metal-cored electrodes described herein, the cores do not contain additional fluxing agents.

It will be appreciated that metal-cored electrodes and flux-cored electrodes are further distinguishable based on the resulting bead characteristics. According to various embodiments, metal-cored electrodes described herein produce slag islands on the face of the resulting weld bead. In contrast, flux-cored electrodes produce extensive slag coverage of the face of the resulting weld bead. For example, slag islands produced by metal-cored electrodes may cover less than 50%, 30% or 10% of the surface area of the weld bead. In contrast, slags produced by flux-cored electrodes may cover more than 50%, 70% or 90% of the surface area of the weld bead. While the amount and the arrangement of the alkaline earth metal in the electrodes may be more advantageous when present in the cores of metal-cored electrodes for high speed welding, embodiments are not so limited and the concepts described herein can be used in other electrode configurations, e.g., flux-cored electrodes.

FIG. **4** is a schematic illustration of a metal-cored electrode wire **40** having a core comprising one or more alkaline earth metal elements (Be, Mg, Ca, Sr, Ba, Ra), according to embodiments. The metal-cored electrode wire **40** includes a sheath **44** formed of a first base metal. The first base metal composition of the sheath **44** can include any one of the steel or aluminum compositions described above with respect to the electrode **20** of FIG. **2A**. The metal-cored electrode **40** additionally includes a core **48** which includes particles **40a** that include a second base metal composition and/or one or more alkaline earth metal elements according to any one or

combination of configurations described above with respect to the particles **32** of FIG. **3A** or particles **36a, 36b** of FIG. **3B**. The core **48** of the metal-cored electrode **40** additionally includes one or more fluorine-containing particles **40b**, according to embodiments. In some other embodiments, the core **48** additionally includes one or more non fluorine containing particles **40c**.

Without being bound to any theory, fluorine-containing compounds within fluorine-containing particles **40b** are used to modify the properties of the slag to improve the shape of the bead, e.g., to reduce the tendency of gas tracking on the formed weld bead. For example, gas tracking, which is a phenomenon observed wherein craters resembling worms are observed on the surface of the weld bead, may be reduced when the fluorine-containing compounds are present. Without being bound to any theory, gas tracking can be observed, e.g., in fast freezing slag systems (rutile based) where the slag solidifies much faster than the weld pool. Due to the rapid solidification of the slag, the gas evolving from the molten weld is partially trapped and thus forms craters on the weld bead surface.

Without being bound to any theory, fluorine containing compounds within the fluorine-containing particles **40b** can also reduce the melting point of slag. The lower melting point of the slag allows the slag to remain molten for a longer time thereby allowing more time for gases to evolve from the molten weld and to dissolve in the slag. The inclusion of fluorine in the slag can also promote the formation of HF, thereby reducing hydrogen from the weld, which decreases the partial pressure of hydrogen in the weld system to reducing the incidence of gas tracking.

The fluorine-containing particles **40b** can include a fluoro-polymer, according to some embodiments. When the fluorine-containing compound includes a fluoro-polymer, the fluoro-polymer can be a homopolymers of hydrocarbon monomers containing 2 to about 10 carbon atoms, where each monomer is substituted by at least one fluorine atom. For example, the fluoro-polymer, can be formed of polychlorotrifluoroethylene, polyvinylidene fluoride, polyvinyl fluoride, the fluorocarbon polymers such as polytetrafluoroethylene and polyhexafluoropropylene, and copolymers such as the copolymers of vinylidene fluoride and tetrafluoroethylene with hexafluoropropylene.

In embodiments, the fluoropolymer polymer has a melting point less than about 1,000° F. such that it may be incorporated into the core **48** in particulate form and retain its composition during forming and drawing of the electrode. It will be appreciated that it may be more impractical to employ the fluoro-polymers in a solid metal wire electrode as described above with respect to FIG. **2A** because polymer may decompose during melting or alloying processes used for producing the solid wire.

In various embodiments disclosed herein, the concentration of fluorine (F) in the electrode wire is between about 0.02 wt % and about 2 wt %, between about 0.1 wt % and about 1.5 wt %, or between about 0.5 wt % and about 1.0 wt %, on the basis of the total weight of the electrode wire, for instance about 0.7 wt %.

Other embodiments are possible, wherein the fluorine-containing particles **40b** include non-polymeric or inorganic fluorine-containing compounds, such as aluminum fluoride, barium fluoride, bismuth fluoride, calcium fluoride, manganese fluoride, potassium fluoride, sodium fluoride, strontium fluoride, polytetrafluoroethylene (such as Teflon®), Na₂SiF₆, K₂SiF₆, Na₃AlF₆ and/or K₃AlF₆; however, it will be appreciated that other or additional fluorine containing compounds can be used.

The non fluorine-containing particles **40c** include a transition metal oxide, e.g., titanium oxide (e.g., rutile, etc.) and/or a transition metal containing compound (e.g., potassium silico-titanate, sodium silico-titanate, etc.), according to embodiments. Generally, the weight percent of the non fluorine-containing particles is greater than the weight percent of the fluorine containing compound, at a ratio between about 0.5-10:1, typically about 0.5-5:1, and more typically about 0.7-4:1, for example.

Arc Welding System Adapted for High Deposition Rates

FIG. **5** illustrates an arc welding system **50** configured for use with welding electrodes discussed supra to deposit weld metal at rates of ~30 lbs/hr or higher for open-arc welding, according to embodiments. In particular, the arc welding system **50** is configured for GMAW, FCAW, FCAW-G, GTAW, SAW, SMAW, or similar arc welding processes that can use a welding electrode comprising an alkaline earth metal, according to embodiments. The arc welding system **50** comprises a welding power source **52**, a welding wire drive **54**, a shielding gas supply **58**, and a welding gun **59**. The welding power source **52** is configured to supply power to the welding system **50** and is electrically coupled to the welding wire drive **54** such that the weld electrode wire serves as a first electrode, and is further electrically coupled to a workpiece **57** which serves as a second electrode, as depicted in detail FIG. **1**. The welding wire drive is coupled to the welding gun **59** and is configured to supply welding electrode wire from the electrode supply **56** to the welding gun **59** during operation of the welding system **50**. In some implementations, the welding power source **52** may also couple and directly supply power to the welding gun **59**.

It will be appreciated that, for illustrative purposes, FIG. **5** shows a semi-automatic welding configuration in which an operator operates the welding torch. However, the metal-cored electrodes described herein can be advantageously used in a robotic welding cell, in which a robotic machine operates the welding torch.

The welding power source **52** includes power conversion circuitry that receives input power from an alternating current power source (e.g., an AC power grid, an engine/generator set, or a combination thereof), conditions the input power, and provides DC or AC output power to the welding system **50**. The welding power source **52** may power the welding wire drive **54** that, in turn, powers the welding gun **59**. The welding power source **52** may include circuit elements (e.g., transformers, rectifiers, switches, and so forth) configured to convert the AC input power to a DC positive or a DC negative output, DC variable polarity, pulsed DC, or a variable balance (e.g., balanced or unbalanced) AC output. It will be appreciated that the welding power source **52** is configured to provide output current between about 100 amps and about 1000 amps, or between about 400 amps and about 800 amps, such that weld metal deposition at rates exceeding about 30 lbs/hr can be achieved.

The shielding gas supply **58** is configured to supply a shielding gas or shielding gas mixtures from one or more shielding gas sources to the welding gun **59**, according to embodiments. A shielding gas, as used herein, may refer to any gas or mixture of gases that may be provided to the arc and/or weld pool in order to provide a particular local atmosphere (e.g., to shield the arc, improve arc stability, limit the formation of metal oxides, improve wetting of the metal surfaces, alter the chemistry of the weld deposit, etc.). In certain embodiments, the shielding gas flow may be a shielding gas or shielding gas mixture (e.g., argon (Ar), helium (He), carbon dioxide (CO₂), oxygen (O₂), nitrogen

(N₂), similar suitable shielding gases, or any mixtures thereof). For example, a shielding gas flow may include Ar, Ar/CO₂ mixtures, Ar/CO₂/O₂ mixtures, Ar/He mixtures, to name a few.

The wire drive **54** may include a permanent magnet motor for providing good control over starting, stopping and speed of wire feed. To enable high weld metal deposition rates exceeding about 30 lbs/hr, the wire drive **54** is configured to provide a wire feed speed between about 50 inches per minute (ipm) and about 2000 ipm, between about 400 ipm and about 1200 ipm, or between about 600 ipm and about 1200 ipm.

In operation, the welding gun **59** receives the welding electrode from the wire drive **54**, power from the welding wire drive **54**, and a shielding gas flow from the shielding gas supply **58** to perform arc welding on a workpiece **57**. The welding gun **59** is brought sufficiently close to the workpiece **57** such that an arc is formed between the consumable welding electrode and the workpiece **57**, as described supra with respect to FIG. **1**. As discussed supra, by controlling the composition of the welding electrode, the chemistry of the arc and/or the resulting weld (e.g., composition and physical characteristics) may be varied.

High Deposition Rate Arc Welding

Referring to FIG. **6**, a method of metal arc welding **60** is described. The method **60** includes providing **62** a consumable welding wire configured to serve as an electrode, where the conductive wire comprises one or more alkaline earth metal elements at a concentration between 0.005% and 10% on the basis of a total weight of the metal-core wire. The atoms of the one or more alkaline earth metal elements are alloyed with a base metal composition. The method **60** additionally includes applying **64** a current to generate a plasma arc sufficient to produce a steady stream of molten droplets formed of the material of the welding wire. The method **60** further includes depositing **66** the molten droplets onto a workpiece at a deposition rate exceeding 25 pounds per hour.

In the method **60**, providing **62** the consumable welding wire comprises providing any welding wire described above, e.g., with respect to FIGS. **2A**, **3A**, **3B** and **4**.

In the method **60**, applying the current **64** includes applying an average current between about 300 amps and about 600 amps, between about 400 amps and about 700 amps, or between about 500 amps and about 800 amps to maintain an average number of plasma instability events are maintained below about 10 events per second, according to some embodiments. According to some other embodiments, applying the current **64** includes applying a peak current between about 400 amps and about 700 amps, between about 500 amps and about 800 amps, or between about 600 amps and about 900 amps.

In the method **60**, depositing **66** includes depositing at a deposition rate exceeding about 20 lbs/hr, 30 lbs/hr, 40 lbs/hr or 50 lbs/hr, according to some embodiments. In some other embodiments, depositing **66** includes depositing at a deposition rate between about 20 lbs/hr and about 70 lbs/hr, between about 30 lbs/hr and about 80 lbs/hr, between about 40 lbs/hr and about 90 lbs/hr, or between about 50 lbs/hr and about 100 lbs/hr, according to embodiments. Such deposition rate can be achieved by applying the current levels described above in conjunction with wire feed speed between about 200 m/min and about 400 m/min, between about 300 m/min and about 500 m/min or between about 400 m/min and about 600 m/min, according to embodiments.

FIG. **7** is a graph **70** illustrating experimental arc instability monitoring result of an electrode wire comprising one

or more alkaline earth metal elements, according to embodiments. The y-axis represents number of instability events per second while the x-axis represents an average current passed through welding electrodes. As described herein, an arc instability event is defined as an event during a sustained deposition arc in which the deposition current, as measured between the consumable electrode and the workpiece, rapidly changes by more than about 3 standard deviations of the average value. In practice, such instability events negatively affect the weld bead's appearance and the mechanical properties, and welding is performed at current values in which such events occur as least frequently as possible.

Still referring to FIG. 7, the monitoring result **74** is that of an arc welding electrode according to an embodiment. In particular, the welding electrode used was a cored welding wire comprising alkaline earth metal elements and a base metal composition based on a steel composition. The welding electrode used to generate the monitoring result **74** was a 1.4 mm diameter electrode which contained 0.12 wt % Ca alloyed with the steel composition, 0.12 wt % Ba alloyed with the steel composition and 0.7% fluorine in the form of polytetrafluoroethylene, according to one embodiment. Comparatively, a welding electrode used to generate the monitoring result **72** was a 1.4 mm diameter which had a similar composition as the welding electrode used to generate monitoring result **74**, except, the control electrode did not contain Ca, Ba nor fluorine in the form of polytetrafluoroethylene.

For both monitoring results **74** and **72**, the welding electrodes were welded robotically using a constant voltage (CV) mode between about 24V and about 37V, using the same mild steel T-joint (horizontal fillet) and same set of welding parameters. For all individual welds, instantaneous welding voltage and current were recorded at 20 kHz frequency (20,000 samples per second). As described herein, an arc instability event (or voltage instability event) refers to an instantaneous drop in welding voltage (from the set-point voltage) to a value below about 10 Volts. Without being bound to any theory, such arc instability events may correspond to instances of deviations from what is commonly referred to as a "spray transfer" mode of metal transfer. As illustrated, in the monitoring result **72**, the number of arc instability events reduces dramatically to less than about 20 at an average current of about 300 amps, and to about zero at an average current of about 500 amps. In contrast, in the monitoring result **74** of the control electrode, the number of arc instability events reduces dramatically to less than about 10 at an average current of about 200 amps, and to about zero at an average current of about 250 amps. That is, it will be appreciated that optimal operational regime for the electrodes having the alkaline earth metal elements according to embodiments is at higher deposition rates and higher current values, compared to control electrodes that do not have the alkaline earth metal elements. In particular, the optimal operational current values for achieving high deposition rates using electrodes according to embodiments is at least 100-200 amps higher than those for using control electrodes that do not have the alkaline earth metal elements.

Power Regulated High Deposition Rate Arc Welding

As described above, there are many challenges associated with welding at very high deposition rates in open-arc welding, e.g. deposition rates of ~30 lbs/hr or higher. The inventors have observed that, when conventional welding wires are used to achieve such high deposition rates, the quality of the resulting weld beads are unacceptable, e.g., due to unacceptable levels of porosity, poor appearance and inferior mechanical properties, e.g., low yield strength,

ductility and fracture toughness. The low quality of the weld beads is often correlated with instabilities observed in the plasma arc during open-arc welding. As described above, according to various embodiments, high quality weld beads can be produced at these very high deposition rates by improving the physical designs and compositions of the electrode wires, e.g., by incorporating alkaline earth metal elements in the welding wire. By using the welding wires comprising alkaline earth metal elements according to embodiments, high deposition rates can be achieved while also producing high quality weld beads. The inventors have observed that the high quality of beads is correlated to the stability of plasma arc during arc welding.

In addition to improving physical designs and compositions of consumables, the inventors have discovered that further improvements in the plasma stability and the quality of the resulting weld bead can be achieved by actively controlling to reduce fluctuations and instabilities in the plasma arc. In particular, the inventors have discovered that reducing fluctuations of power delivered to the plasma arc can be particularly effective in improving the quality of the weld bead. The power fluctuations can in turn be reduced by regulating power to maintain a substantially constant power delivered to the plasma arc.

In various open arc-welding technologies, power is delivered to the plasma arc using a constant current (CC) mode or a constant voltage (CV) mode. Under the CC mode, the power delivery circuitry varies its output voltage to maintain a relatively constant current. Under the CV mode, the power delivery circuitry varies its output current to maintain a relatively constant voltage. A CV mode may be advantageous, e.g., in techniques where the arc distance may not be easily controllable. A CC mode may be advantageous, e.g., in techniques where a fixed number of amps reaching the material to be welded is needed regardless of the arc distance. For example, some shielded metal arc welding and gas tungsten arc welding techniques use a CC modes, while some gas metal arc welding and flux-cored arc welding techniques use CV modes.

The inventors have discovered that, further improvements in plasma stability and/or the quality of weld beads can be achieved at high deposition rates, e.g., rates exceeding ~30 lbs./hr., when, instead of using CV or CC modes, power delivered to the plasma arc is actively regulated to be relatively constant during deposition. When power is regulated during deposition according to embodiments, the standard deviation of power can be significantly reduced. The inventors have discovered that the magnitude of standard deviation of power during arc welding exhibits a stronger correlation with plasma instabilities that lead to poor bead qualities, compared to the magnitudes of standard deviations of current or voltage. Accordingly, in the following, methods and systems of power-regulated arc welding are described, which can advantageously improve the plasma stability and/or the quality of weld beads, with or without the use of alkaline earth metal-containing weld electrodes.

FIG. 8 illustrates a comparison of experimental wave forms generated during power-regulated arc welding according to embodiments against wave forms generated during a constant voltage arc welding. The top, middle and bottom graphs illustrate voltage (V), current (A) and power (W) waveforms as functions of time, respectively. For illustrative purposes, the mode of regulation was switched during a continuous weld session using a continuous welding wire. The welding wire used was a metal cored welding wire comprising alkaline earth metal elements and a base metal composition based on a steel composition, similar to that

used in generating the experimental results in FIG. 7. The welding wire was fed at a rate of 850 inches per minute while a target power of 32 kW was delivered to the plasma arc, resulting in a deposition rate of 38 lbs/hr. The left waveform region **810** illustrates a region during which arc welding was performed under a power regulation mode according to various embodiments, and the right waveform region **820** illustrates a region during which arc welding was performed under a constant voltage (CV) mode. As illustrated by the waveform region **810**, under the power regulation mode, the voltage and current fluctuate at relatively higher amplitudes, while the power fluctuates at relatively lower amplitudes. In contrast, as illustrated by the waveform region **820**, under the conventional CV mode, the voltage fluctuates at relatively lower amplitude, while the power fluctuates at relatively higher amplitudes. The observed standard deviations of power in the power regulation waveform region **810** and in the CV mode region **820** are about 250 W and 1000 W, respectively. The inventors have discovered that, among fluctuations in voltage, current and power, the fluctuation in power has the strongest correlation to plasma instabilities that lead to bead quality degradation. Thus, advantageously, according to various embodiments described herein, methods of arc welding regulate power such that the standard deviation in power is kept relatively low compared to CV and CC modes.

FIG. 9 illustrates a method **900** of arc welding by regulating power, according to various embodiments. The method **900** includes providing **910** a welding wire adapted for arc welding at a high deposition rate. Although embodiments are not so limited, the welding wire comprises one or more alkaline earth metal elements. The method **900** additionally includes applying **920** power to the welding wire to generate a plasma arc sufficient to melt the welding wire. The method **900** further includes depositing **930** molten droplets formed by melting the welding wire onto a work-piece at the high deposition rate. The deposition is carried out while regulating to maintain a substantially constant power delivered to the plasma arc.

As described herein, a high deposition rate in the context of power regulated arc welding refers to a deposition rate exceeding about 20 lbs/hr, 30 lbs/hr, 40 lbs/hr or 50 lbs/hr, or a deposition rate disclosed anywhere in the application, or in a range defined by any of these values, according to some embodiments. In some other embodiments, depositing **66** includes depositing at a deposition rate between about 20 lbs/hr and about 70 lbs/hr, between about 30 lbs/hr and about 80 lbs/hr, between about 40 lbs/hr and about 90 lbs/hr, or between about 50 lbs/hr and about 100 lbs/hr, according to embodiments.

The high deposition rate can be achieved by regulating the power delivered to the plasma arc during arc welding, which can have an average value exceeding 10 kW, 15 kW, 20 kW, 25 kW, 30 kW, 35 kW, 40 kW, 45 kW, 50 kW, 55 kW or 60 kW, or have any other value disclosed anywhere in the application, or have a value in a range defined by any of these values, according to embodiments.

To regulate the power, a suitable amount of current is delivered to the plasma arc and/or measured therefrom, which can have an average value exceeding about 200 amps, 300 amps, 400 amps, 500 amps, 600 amps, 700 amps, 800 amps, 900 amps or 1000 amps, or have any other value disclosed anywhere in the application, or have an average value in a range defined by any of these values, according to embodiments.

To regulate the power, a suitable voltage is delivered to the plasma arc and/or measured therefrom, which can have

an average value exceeding about 20V, 25V, 30V, 35V, 40V, 45V, 50V, 55V, 60V, 65V, 70V, 75V or 80V, or have any other value disclosed anywhere in the application, or have a value in a range defined by any of these values, according to embodiments.

The target deposition rate may be achieved by regulating the power at the above-indicated values, while continuously feeding the welding wire at a speed between about 200 m/min and about 400 m/min, between about 300 m/min and about 500 m/min, between about 400 m/min and about 600 m/min, or at a speed disclosed anywhere in the application, or at a speed having a value in a range defined by any of these values, according to embodiments.

In some embodiments, the feeding speed of the welding electrode (wire or stick) can be actively varied or adjusted during an arc welding session in combination with the regulation of power. By allowing the wire feeder to adjust wire feed speed via an active feedback of either current or voltage, the current or voltage can be maintained relatively constant while maintaining the low standard deviation of power. In a related manner, in some embodiments, a contact tip to work distance (CTWD) can be actively varied or adjusted during an arc welding session in combination with the regulation of power. Similar to the feeding speed adjustment, the CTWD can be adjusted via a feedback of either current or voltage, thereby allowing the current or voltage to be maintained relatively constant while maintaining the low standard deviation of power.

The inventors have found that regulating power, compared to regulating voltage or current, can result in a significant improvement in standard deviation of power. The resulting relatively low standard deviation can in turn result in a significant improvement of the stability of the plasma arc and bead quality. As illustrated above with respect to FIG. 8, for similar nominal power levels, regulating power results in a substantially smaller standard deviation of power.

The inventors have found that, according to embodiments, the standard deviation of power delivered to the plasma arc at a target average power can have a value below about 600 W, 550 W, 500 W, 450 W, 400 W, 350 W, 300 W, 250 W, 200 W, 150 W or 100W, or a value in a range defined by any of these values. The standard deviation of power can also have a percentage of the target average power that is below about 2%, 1.5%, 1%, or 0.5%, or a value in a range defined by any of these values. As described herein, the power delivered to the plasma arc is referred to as being substantially constant when the standard deviation has any of these values. These standard deviation values can be maintained, according to the methods described herein, for a duration exceeding 100 msec, 200 msec, 500 msec or 1 sec, or for a duration in a range defined by any of these values, for instance the entire duration of the power-regulated arc welding session.

According to various embodiments of the methods and systems of power-regulated arc welding, any welding wire described herein can be used. Any welding wire comprising one or more alkaline earth metal elements can be particularly suitable for power-regulated arc welding as described herein. However, embodiments are not so limited and any welding wire suitable for welding at a high deposition rate disclosed herein can be used.

The methods of power-regulated arc welding according to embodiments may be implemented using a suitable arc welding system, e.g., one similar to the arc welding system **50** illustrated above with respect to FIG. 5, which may be configured for GMAW, FCAW, FCAW-G, GTAW, SAW, SMAW, or similar arc welding processes. In particular, the

welding power source **52**, which is configured to supply power to the welding system **50** and is electrically coupled to the welding wire drive **54** such that the weld electrode wire serves as a first electrode, is configured to supply a relatively high power for high deposition rates and to regulate the power during arc welding according to various embodiments by, e.g., providing a power source **52** that is adapted for power regulation. The system **50** may further be adapted for arc welding by feeding a suitable welding wire, e.g., welding electrode wires comprising an alkaline earth metal, at a sufficient rate while delivering sufficient power such that a high deposition rate is achieved.

FIGS. **10A** and **10B** illustrate a comparison of experimental waveforms generated during power-regulated arc welding (FIG. **10A**) according to embodiments and a constant voltage arc welding (FIG. **10B**). The top, middle and bottom graphs of each of FIGS. **10A** and **10B** illustrate voltage (V), current (A) and power (W) in the y-axes, as a function of time in the x-axes, respectively. The waveforms span 240 milliseconds between the cursors. The experimental conditions and the welding wire used to obtain the results of FIG. **10A** were similar to those used to obtain the waveform region **810** in FIG. **8**, which was measured under a power regulation mode according to embodiments. The experimental conditions and the welding wire used to obtain the results of FIG. **10B** were similar to those used to obtain waveform region **820** in FIG. **8**, which was measured under a constant voltage (CV) mode. Similar to the waveform region **810** illustrated with respect to FIG. **8**, FIG. **10A** illustrates that under the power regulation mode, the voltage and current fluctuate at relatively higher amplitudes, while the power fluctuates at relatively lower amplitudes. In contrast, similar to the waveform region **820** illustrated with respect to FIG. **8**, under the constant voltage mode, the voltage fluctuate at relatively lower amplitudes, while the power fluctuates at relatively higher amplitudes. The observed standard deviations of power in the waveform corresponding to power regulation mode illustrated with respect to FIG. **10A** and in waveform corresponding to CV mode illustrated with respect to FIG. **10B** were about 60 and 1060 W, respectively. Surge Limited Power Regulation During High Deposition Rate Arc Welding

In the above, power regulation during arc welding has been described, which results in various improvements of the plasma arc characteristics including reduced standard deviation of the power delivered to the plasma arc, which in turn improves various aspects of the bead quality including reduced porosity. In addition to a baseline standard deviation of power, the inventors have additionally discovered that reducing instantaneous spikes or surges in current, voltage and/or power delivered to the plasma arc can also greatly improve the plasma arc characteristics and the resulting bead quality.

FIG. **11A** illustrates experimental waveforms generated during power-regulated arc welding, according to embodiments. The top, middle and bottom graphs of FIG. **11A** illustrate voltage (V), current (A) and power (W) in the y-axes, as a function of time in the x-axes, respectively. The plasma arc was power-regulated at a target power of 32K Watts. Referring to the top graph, the voltage waveform shows a spike in voltage from about 50V to 75V within a short time span of about 250 microseconds. In response to the voltage spike, referring to the middle graph, the power supply attempted to compensate for the instantaneous reduction in the delivered power by rapidly decreasing the current value by more than 150 amps. In part due to the limited response time of the circuit of the power supply to respond

to the rapid change in voltage, the range of power delivered to the plasma arc spanned about ± 3000 Watts relative to the target or average power.

FIG. **11B** illustrated an example embodiment of power regulated arc welding method **1100** including limiting an amount of change in current to control surges and spikes of power, according to embodiments. Embodiments of arc welding comprises applying power to a welding wire to generate a plasma arc sufficient to melt the welding wire according to various embodiments described herein, and depositing molten droplets formed by melting the welding wire onto a workpiece at a high deposition rate, e.g., exceeding 30 pounds per hour. According to the illustrated embodiment, the method **1100** of arc welding comprises beginning regulation **1110** of power at a preset power. The deposition is performed while regulating power delivered to the plasma arc according to various embodiments disclosed herein. The method additionally comprises detecting **1120** a change in voltage over time, e.g., instantaneous change in voltage (dV/dt), wherein detecting comprises detecting a dV/dt that exceeds a predetermined value. The method further includes, upon determination that the dV/dt exceeds the predetermined value, limiting the amount of change in current to a predetermined value.

Still referring to FIG. **11B**, detecting **1120** the dV/dt includes detecting a voltage change per unit time which exceeds 0.05 V/microsecond, 0.1 V/microsecond, 0.2 V/microsecond, 0.4 V/microsecond, 0.6 V/microsecond, 0.8 V/microsecond, or 1.0 V/microsecond, or a value in a range defined by any of these values. Alternatively, detecting **1120** the dV/dt can also include detecting a percentage of the average power which exceeds 0.2%/microsecond, 0.4%/microsecond, 0.8%/microsecond, 1.2%/microsecond, 1.6%/microsecond, or 2.0%/microsecond, or a value in a range defined by any of these values, according to embodiments.

Still referring to FIG. **11B**, limiting **1130** a rapid change, e.g., a spike or a dip in current, includes limiting the change to less than about 400 amps, 350 amps, 300 amps, 250 amps, 200 amps, 150 amps, 100 amps, 50 amps, or about 0 amps, or a value in a range defined by any of these values, according to embodiments. Alternatively, limiting **1130** a change or a spike in current includes limiting the change to less than about 100%, 80%, 60%, 40%, 20%, 10%, or about 0%, or a percentage in a range defined by any of these values, according to embodiments.

Still referring to FIG. **11B**, limiting **1130** a change or a spike in current includes implementing the limit for a duration less than 1000 μs , 800 μs , 600 μs , 400 μs , 200 μs , or 100 μs , or a value in a range defined by any of these values, according to embodiments.

Embodiments

1. A consumable metal-cored welding wire configured to serve as an electrode during metal arc welding, the welding wire comprising:
 - a sheath having a first base metal composition;
 - a core surrounded by the sheath and comprising particles having a second base metal composition alloyed with one or more alkaline earth metal elements at a concentration between 0.005% and 10% on the basis of a total weight of the welding wire.
2. The welding wire of Embodiment 1, wherein, when present, non-metallic atomic elements in the core are present at a concentration not exceeding 5% on the basis of the total weight of the welding wire.

3. The welding wire of Embodiment 1, wherein the concentration of the one or more alkaline earth metal elements is between 0.005% and 0.5% on the basis of the total weight of the welding wire.
4. The welding wire of Embodiment 2, wherein the first base metal composition and the second based metal composition comprise different metal or metal alloy compositions.
5. The welding wire of Embodiment 2, wherein the first base metal composition and the second based metal composition comprise the same metal or metal alloy compositions.
6. The welding wire of Embodiment 2, wherein the one or more alkaline earth metal elements comprise Ba.
7. The welding wire of Embodiment 6, wherein the one or more alkaline earth metal elements further comprise Ca.
8. The welding wire of Embodiment 2, wherein the welding wire is configured for gas metal arc welding (GMAW), wherein the core does not include an additional fluxing agent.
9. The welding wire of Embodiment 2, wherein the metal-core welding wire is configured for gas metal arc welding (GMAW), wherein the core further comprises a fluoropolymer at a concentration not exceeding 2% on the basis of the total weight of the welding wire.
10. The welding wire of Embodiment 8, wherein the fluxing agent further comprises a transition metal oxide.
11. A method of metal arc welding, comprising:
 - providing a consumable cored welding wire configured to serve as an electrode, the welding wire comprising one or more alkaline earth metal elements at a concentration between 0.005% and 10% on the basis of a total weight of the welding wire, wherein the atoms of the one or more alkaline earth metal elements are alloyed with a base metal composition;
 - applying a current to generate a plasma arc sufficient to produce a steady stream of molten droplets of the welding wire; and
 - depositing the molten droplets onto a workpiece at a deposition rate exceeding 30 pounds per hour.
12. The method of Embodiment 11, wherein the consumable welding wire is a metal-cored welding wire having a core surrounded by a sheath, wherein the core comprises particles having the base metal composition that is alloyed with the one or more alkaline earth metal elements.
13. The method of Embodiment 12, wherein the method is a gas metal arc welding (GMAW), wherein the core does not include an additional fluxing agent and when present, includes non-metallic atomic elements at a concentration not exceeding 5% on the basis of the total weight of the welding wire.
14. The method of Embodiment 13, wherein the non-metallic atomic elements are present at a concentration such that, depositing the molten droplets onto the workpiece comprises forming slag islands on a surface of a resulting weld bead without substantially covering the entire surface of the resulting weld bead.
15. The method of Embodiment 12, wherein the method is a gas metal arc welding (GMAW), wherein the core further comprises a fluoropolymer.
16. The method of Embodiment 15, wherein the fluoropolymer is present at a concentration not exceeding 2% on the basis of the total weight of the welding wire.
17. The method of Embodiment 11, wherein applying the current comprises applying an average current between about 400 amps and about 700 amps to maintain an average number of plasma instability events below about 10 events per second.

18. A system for metal arc welding, comprising:
 - a consumable cored welding wire configured to serve as an electrode, the welding wire comprising one or more alkaline earth metal elements at a concentration between 0.005% and 10% on the basis of a total weight of the welding wire, wherein the atoms of the one or more alkaline earth metal elements are alloyed with a base metal composition;
 - a power source configured to apply a current to generate a plasma arc sufficient to produce a steady stream of molten droplets of the welding wire; and
 - a weld gun configured to deposit the molten droplets onto a workpiece at a deposition rate exceeding 30 pounds per hour.
19. The system of Embodiment 18, wherein the consumable welding wire is a metal-cored welding wire having a core surrounded by a sheath, wherein the core comprises particles having the base metal composition that is alloyed with the one or more alkaline earth metal elements.
20. The system of Embodiment 19, wherein the power source is configured to apply an average current between about 400 amps and about 700 amps to maintain an average number of plasma instability events during welding below about 10 events per second.
21. A method of arc welding, comprising:
 - providing a welding wire comprising one or more alkaline earth metal elements; applying power to the welding wire to generate a plasma arc sufficient to melt the welding wire; and
 - depositing molten droplets formed by melting the welding wire onto a workpiece at a deposition rate exceeding 30 pounds per hour while regulating to maintain a substantially constant power delivered to the plasma arc.
22. The method of Embodiment 21, wherein the concentration of the one or more alkaline earth metal elements in the welding wire is between 0.005% and 10% on the basis of a total weight of the welding wire.
23. The method of anyone of Embodiments 21-22, wherein the welding wire is a metal-cored welding wire comprising a sheath and a core surrounded by the sheath, wherein the core comprises the one or more alkaline earth metal elements.
24. The method of any one of Embodiments 21-23, wherein the core comprises particles having a first base metal composition that is alloyed with the one or more alkaline earth metal elements.
25. The method of any one of Embodiments 21-23, wherein, when present, non-metallic atomic elements in the core are present at a concentration not exceeding 5% on the basis of the total weight of the welding wire.
26. The method of any one of Embodiments 21-25, wherein the method is a gas metal arc welding (GMAW), wherein the core further comprises a fluoropolymer.
27. The method of any one of Embodiments 21-26, wherein the alkaline earth metal comprises one or more of Ba or Ca.
28. The method of any one of Embodiments 21-27, wherein the welding wire is according to any one of Embodiments 1-10.
28. The method of any one of Embodiments 21-27, wherein the method is according to any one of Embodiments 11-17.
29. The method of any one of Embodiments 21-27, wherein the method is performed using the system according to any one of Embodiments 18-20.

30. A method of arc welding, comprising:
 applying power to a welding wire to generate a plasma arc sufficient to melt the welding wire; and
 depositing molten droplets formed by melting the welding wire onto a workpiece at a deposition rate exceeding 30 pounds per hour, wherein depositing is performed while regulating power delivered to the plasma arc such that a standard deviation of the power delivered to the plasma arc is less than 2% of an average power delivered to the plasma arc.
31. The method of Embodiment 30, wherein the standard deviation of the power is less than 500 Watts (W) over a period of at least 200 milliseconds.
32. The method of Embodiments 30-31, wherein regulating the power includes regulating at greater than 20 kW.
33. The method of Embodiments 30-32, wherein regulating the power comprises delivering to the plasma arc an average current exceeding about 500 amps (A) and an average voltage exceeding about 40 volts (V).
34. The method of Embodiments 30-33, wherein regulating the power is such that an average number of plasma instability events is below about 10 events per second.
35. The method of Embodiments 30-34, wherein the arc welding is a gas metal arc welding (GMAW).
36. The method of Embodiments 30-35, wherein the welding wire comprises one or more alkaline earth metal elements at a concentration between 0.005% and 10% on the basis of a total weight of the welding wire.
37. The method of Embodiments 30-36, wherein the welding wire is a metal-cored welding wire comprising a sheath and a core surrounded by the sheath, wherein the core comprises the one or more alkaline earth metal elements.
38. The method of Embodiments 30-37, wherein regulating the power includes actively adjusting a feeding speed or a contact to work distance (CTWD) of the welding wire based on a feedback of current or voltage measured from the plasma arc.
39. The method of any one of Embodiments 30-38, wherein the welding wire is according to any one of Embodiments 1-10.
40. The method of any one of Embodiments 30-38, wherein the method is according to any one of Embodiments 11-17.
41. The method of any one of Embodiments 30-38, wherein the method is performed using the system according to any one of Embodiments 18-20.
42. A method of arc welding, comprising:
 applying power to a welding wire to generate a plasma arc sufficient to melt the welding wire; and
 depositing molten droplets formed by melting the welding wire onto a workpiece at a deposition rate exceeding 30 pounds per hour, wherein depositing is performed while regulating power delivered to the plasma arc,
 wherein regulating power comprises limiting an amount of change in current.
43. The method of Embodiment 42, wherein regulating power comprises detecting an instantaneous change in voltage (dV/dt) exceeding a predetermined value prior to limiting the amount of change in current.
44. The method of Embodiments 42-43, wherein the dV/dt exceeds 0.1 V/microseconds.
45. The method of Embodiments 42-44, wherein limiting the amount of change in current comprises limiting to less than about 200 amps.

46. The method of Embodiments 42-45, wherein limiting the amount of change in current comprises limiting for a predetermined duration less than 1 millisecond.
47. The method of Embodiments 42-46, wherein regulating power comprises regulating power delivered to the plasma arc such that a standard deviation of power is less than 2% of an average power delivered to the plasma arc.
48. The method of Embodiments 42-47, wherein the welding wire comprises one or more alkaline earth metal elements at a concentration between 0.005% and 10% on the basis of the total weight of the welding wire.
49. The method of any one of Embodiments 42-47, wherein the welding wire is according to any one of Embodiments 1-10.
50. The method of any one of Embodiments 42-47, wherein the method is according to any one of Embodiments 11-17.
51. The method of any one of Embodiments 42-47, wherein the method is performed using the system according to any one of Embodiments 18-20.
- In the embodiments described above, apparatus, systems, and methods for high deposition rate arc welding are described in connection with particular embodiments. It will be understood, however, that the principles and advantages of the embodiments can be used for any other systems, apparatus, or methods with a need for high deposition rate arc welding. In the foregoing, it will be appreciated that any feature of any one of the embodiments can be combined and/or substituted with any other feature of any other one of the embodiments.
- Unless the context clearly requires otherwise, throughout the description and the claims, the words "comprise," "comprising," "include," "including" and the like are to be construed in an inclusive sense, as opposed to an exclusive or exhaustive sense; that is to say, in the sense of "including, but not limited to." The word "coupled", as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Likewise, the word "connected", as generally used herein, refers to two or more elements that may be either directly connected, or connected by way of one or more intermediate elements. Additionally, the words "herein," "above," "below," "infra," "supra," and words of similar import, when used in this application, shall refer to this application as a whole and not to any particular portions of this application. Where the context permits, words in the above Detailed Description using the singular or plural number may also include the plural or singular number, respectively. The word "or" in reference to a list of two or more items, that word covers all of the following interpretations of the word: any of the items in the list, all of the items in the list, and any combination of the items in the list.
- Moreover, conditional language used herein, such as, among others, "can," "could," "might," "may," "e.g.," "for example," "such as" and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or states. Thus, such conditional language is not generally intended to imply that features, elements and/or states are in any way required for one or more embodiments or whether these features, elements and/or states are included or are to be performed in any particular embodiment.
- While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the disclosure.

25

Indeed, the novel apparatus, methods, and systems described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the disclosure. For example, while blocks are presented in a given arrangement, alternative embodiments may perform similar functionalities with different components and/or circuit topologies, and some blocks may be deleted, moved, added, subdivided, combined, and/or modified. Each of these blocks may be implemented in a variety of different ways. Any suitable combination of the elements and acts of the various embodiments described above can be combined to provide further embodiments. The various features and processes described above may be implemented independently of one another, or may be combined in various ways. All suitable combinations and subcombinations of features of this disclosure are intended to fall within the scope of this disclosure.

What is claimed is:

1. A method of arc welding, comprising:
 providing a welding wire comprising one or more alkaline earth metal elements;
 applying power to the welding wire to generate a plasma arc sufficient to melt the welding wire; and
 depositing molten droplets formed by melting the welding wire onto a workpiece at a deposition rate exceeding 30 pounds per hour while regulating to maintain a constant power delivered to the plasma arc,
 wherein the welding wire includes a fluoropolymer, and wherein the method is a gas metal arc welding (GMAW).
2. The method of claim 1, wherein the concentration of the one or more alkaline earth metal elements in the welding wire is between 0.005% and 10% based on a total weight of the welding wire.
3. The method of claim 1, wherein the welding wire is a metal-cored welding wire comprising a sheath and a core surrounded by the sheath, wherein the core comprises the one or more alkaline earth metal elements.

26

4. The method of claim 3, wherein the core comprises particles having a first base metal composition that is alloyed with the one or more alkaline earth metal elements.

5. The method of claim 3, wherein, when present, non-metallic atomic elements in the core are present at a concentration not exceeding 5% based on the total weight of the welding wire.

6. The method of claim 5, wherein the core further comprises the fluoropolymer.

7. The method of claim 1, wherein the one or more alkaline earth metal elements comprises one or more of Ba or Ca.

8. A method of arc welding, comprising:

providing a welding wire comprising one or more alkaline earth metal elements;

applying power to the welding wire to generate a plasma arc sufficient to melt the welding wire; and

depositing molten droplets formed by melting the welding wire onto a workpiece at a deposition rate exceeding 30 pounds per hour while regulating to maintain a constant power delivered to the plasma arc,

wherein the welding wire is a metal-cored welding wire comprising a sheath and a core surrounded by the sheath, wherein the core comprises the one or more alkaline earth metal elements, and

wherein, when present, non-metallic atomic elements in the core are present at a concentration not exceeding 5% based on the total weight of the welding wire.

9. A method of arc welding, comprising:

providing a welding wire comprising one or more alkaline earth metal elements;

applying power to the welding wire to generate a plasma arc sufficient to melt the welding wire; and

depositing molten droplets formed by melting the welding wire onto a workpiece at a deposition rate exceeding 30 pounds per hour while regulating to maintain a constant power delivered to the plasma arc,

wherein the welding wire is a metal-cored welding wire comprising a sheath and a core surrounded by the sheath, wherein the core comprises the one or more alkaline earth metal elements, and

wherein the method is a gas metal arc welding (GMAW), and wherein the core comprises a fluoropolymer.

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